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Restructurable Controls

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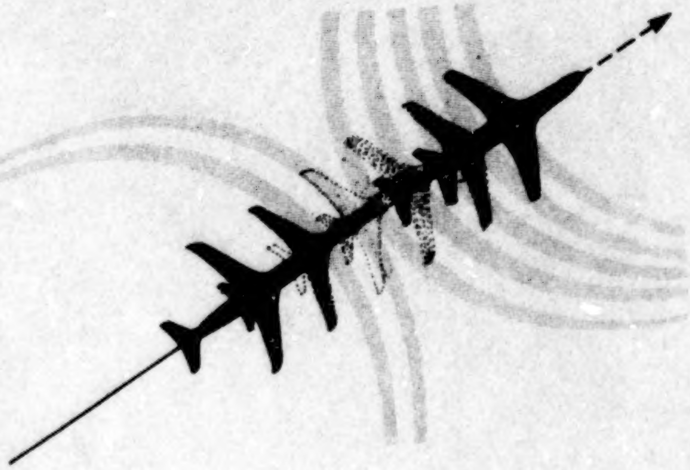

Proceedings of a workshop held at
NASA Langley Research Center
Hampton, Virginia
September 21-22, 1982

25th Anniversary
1958-1983

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Restructurable Controls

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1983

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PREFACE

The motivation to hold a workshop on restructurable controls arose from several recent developments associated with automatic flight control systems in aircraft. First, modern analysis and synthesis procedures are finding increased acceptance in this field, are rapidly maturing, are relatively robust, and are becoming highly automated through the use of interactive computer processes. Second, the ability to obtain the data necessary for the design of aircraft controls is also being automated. Finally, a series of flight tests conducted at NASA Langley Research Center in May 1981 demonstrated the ability to generate complete designs of various autopilots for a specific aircraft on an overnight basis. The flight test results with the newly designed autopilots were excellent.

As an offshoot to these tests, and as a part of an overall program that has become known as restructurable controls, an experiment was conceived to do a completely automated design, within the limits of the procedures, for an assumed unknown aircraft and to do it with minimal intervention of designers. The motivation was to investigate the possibility of using these techniques to augment on-board capability to accommodate unanticipated failures and to assess the possibility of providing industry with an end-to-end design package. The elements of the experiment were:

Identify in flight the aircraft parameters needed for the control system design and do this automatically and in real time

Design in real time the automatic control law using the data obtained above, basing the design on pre-established design procedure and design criteria

Implement and flight test the control law in real time

Notwithstanding some theoretical pitfalls, such as the facts that parameter identification processes do not always converge to the correct set and that much work needs to be done to fully automate the control system design process, researchers at Langley examined what could be done in this area in general and what had been done specifically. We started with a given aircraft and noted that its parameters were available from several sources, including both DATCOM and flight data that were analyzed using various parameter identification algorithms. Data from these sources had been used to design the flight control laws for the aircraft, and they had all worked with varying degrees of success in flight tests. Our conclusion was that the experiment would redo what had already been done with one significant difference: the time scale would be compressed from years to 1 day. A corollary to this conclusion was that it was likely that the same time scale compression in the design procedure could be achieved for a given aircraft about which a reasonable amount of data was available. In fact, if one were concerned in the design with only one flight condition, then the process should take only a few minutes. If this process could be further reduced to a few seconds and the design fully automated, then such a procedure could provide a backup capability that could potentially be useful in future aircraft with flight-crucial controls. The examination of the benefits of such techniques led to a closer study of the technical implications and provided the basis for this workshop.

The potential applications of these possibilities in the real-life experiences cited in the proceedings (the Delta Flight 1080 incident and the American Airlines

DC-10 Chicago accident) and the requirements associated with the implementation of flight-crucial controls in commercial aircraft of the near future laid the groundwork for this workshop.

W. E. Howell, W. T. Bundick, A. J. Ostroff,
R. M. Hueschen, and Christine M. Belcastro
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1.0 INTRODUCTION

1.1 Background

In modern aircraft equipped with sophisticated controls there are an unlimited number of ways in which things can go wrong. Unfortunately to date, there are only a limited number of ways in which some of these things can be corrected. Typically, this correctable set contains problems which can be anticipated and for which appropriately pre-planned procedures and/or actions have been specified, i.e., they are problems for which a set of contingency plans to reconfigure the aircraft or its control mode have been specified. A typical example is the procedure for handling an engine-out condition during takeoff.

The unanticipated problems or failures are the cause of most incidents and/or accidents and present the biggest challenge to the control system designer. Often, accident investigations find that there was a way in which the aircraft could have been saved if the proper actions had been taken in a timely fashion. Because this time frame is typically a few seconds and given the level of stress and confusion during these incidents, it is understandable that a pilot may not find the solution in time to salvage the aircraft.

Furthermore, pressures to realize economic gains are forcing airframe manufacturers to consider aircraft designs with reduced static stability (RSS) and associated automatic control systems of increased complexity and capabilities. While these fly-by-wire (FBW) control systems will undoubtedly incorporate numerous contingency plans to deal with predictable failures, the probability of an unanticipated sequence of events leading the pilot into a situation in which the solution is not intuitively clear is drastically increased. However, with such highly augmented aircraft and with the application of recent theoretical and technological developments, it is probable that the aircraft will be flyable in some mode.

With the emerging theoretical capabilities and the powerful computational capability likely to be available on future aircraft, it appears that the potential exists to effectively provide the equivalent of several months design effort in a few seconds to help mitigate the consequences of unanticipated failures in aircraft. Two examples in which aircraft control system failures were unanticipated but solvable are included in the Appendices. In one case* (Appendix A), the pilot restructured the basic longitudinal control law and successfully landed the aircraft; in the other case (Appendix B), the pilot was unable to do so.

While neither the organizers nor the participants of the workshop wish to single out these two cases as indicative of shortcomings, either from the system or the pilot, they do serve to emphasize the timeliness of the problem we wish to address.

1.2 Framework of Workshop

On September 21 and 22, 1982, the Applied Control Branch, Flight Control Systems Division, Langley Research Center, National Aeronautics and Space Administration organized a workshop on Restructurable Control at the Langley Research Center, Hampton, Virginia.

The purpose of this workshop was to elicit ideas which may be applied to the real time, automatic, "instantaneous fix" of a wide variety of anticipated failures, and, in the not too distant future, to the problem of restructuring in real time the control system of an aircraft following unanticipated failures.

A group of experts from academia and industry in the fields of control theory, aeromechanics, system identification, and related fields were invited to present their perception of the problem and to recommend what combination(s) of the emerging methodologies can be applied to the solution of the problem or parts thereof.

1.3 Problem Definition

The problem can be stated as follows. Upon failure of a control element, the control system is to be restructured in such a way that the aircraft recovers to a safe condition and can then be flown, either manually or automatically, to a safe landing. It is assumed that the failure occurs in a control element(s) but that the flight control computer and the aircraft sensors are fully operational.

---

* The article Flight 1080 which appeared in Airline Pilot (July 1978) has been reproduced in Appendix A by permission of the publisher.

The process of restructuring the control system includes, as a minimum, the detection and identification of the failure(s), identification of the new plant, redesign of the control laws or gains, and generation of information for display to the pilot. Two possible conceptual interactions of these elements are presented in Figure 1.

It should be noted that there is a difference between the concept of reconfigurable controls which is currently under study and the concept of restructurable controls which is being addressed for the first time at this workshop. The principal distinction is the degree of a priori knowledge about the causes and effects of failure. Other distinctions are identified in Table 1.

1.4 Organization and Theme of Proceedings

Included in the following sections of these proceedings are the presentations by the invited speakers to the workshop (Section 2.0) and a summary of the comments made by the attendees to the workshop during the discussion period that followed the presentations (Section 3.0).
The appendices include the Delta Flight 1080 story (Appendix A) and excerpts from the NTSB report on the American Airlines DC-10 crash in Chicago (Appendix B).

The organizers of this workshop hope that other researchers and practitioners will be motivated by the presentations and discussions in these proceedings into exploring and expanding the proposed approaches and into formulating alternate approaches to the problem of restructurable controls. The results of these efforts will be essential to assure that future aircraft will meet or exceed the enviable safety record of today's aircraft.

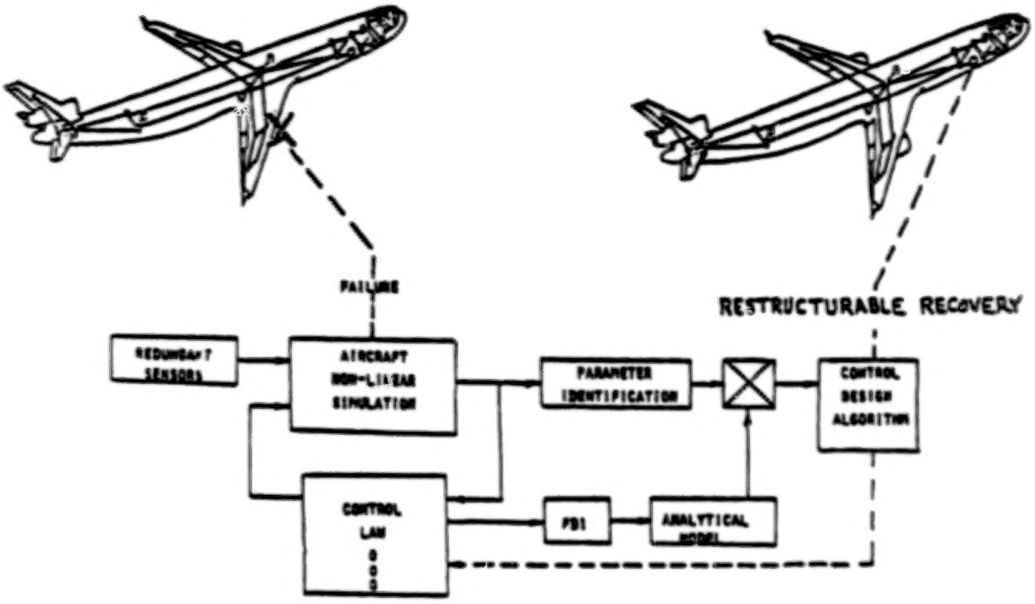
FAILURE
RESTRUCTURABLE RECOVERY
REDUNDANT SENSORS
AIRCRAFT NON-LINEAR SIMULATION
PARAMETER IDENTIFICATION
CONTROL DESIGN ALGORITHM
CONTROL LAW
FDI
ANALYTICAL MODEL

Figure 1. Conceptual Block Diagram of Two Approaches to the Restructurable Control Problem.

Table 1. Differences Between Reconfigurable and Restructurable Controls

Reconfigurable Controls	Restructurable Controls
Loss of given control surfaces anticipated a-priori	Less a priori knowledge assumed
Redistribution of forces and moments attempted from remaining surfaces and engines using previously stored control law	May apply to broader spectrum of problems (i.e., s/w failures)
Near term possible	Long term goal

2.0 PRESENTATIONS

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ON RESTRUCTURABLE CONTROL SYSTEM THEORY

Michael Athans
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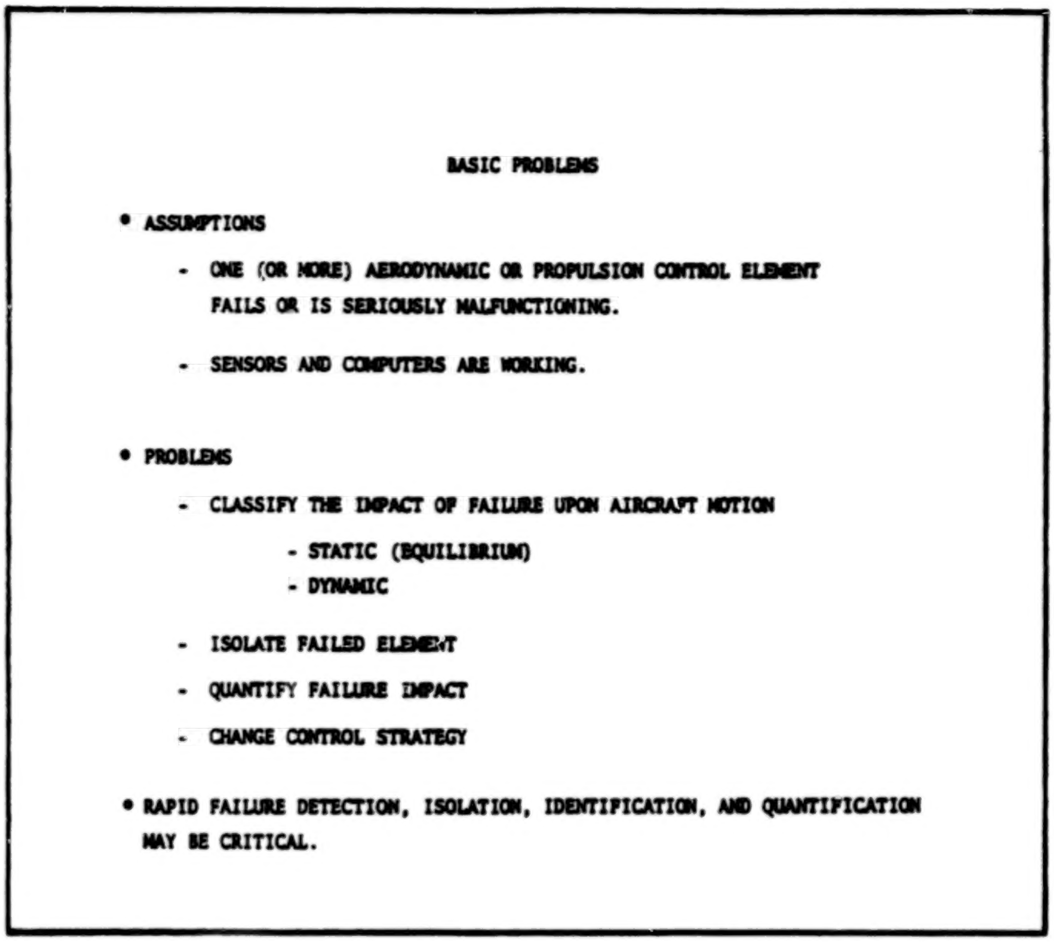
Introductory Remarks

The main theme of my talk is the exposition of the state of stochastic system and control theory as it impacts Restructurable Control issues.

Let me first state the basic assumptions that I am going to make. Effectively I am not going to pay attention at this meeting to the problem of sensor failure detection, because, I think that this problem is well in hand from both a theoretical and pragmatic point of view. Computer failures will also be ignored, since I tend to doubt that the pilot can reprogram the flight control computer.

I will assume that one or more aerodynamic or propulsion control elements or some part of the structure fails or is seriously malfunctioning. I also assume that the sensors that can help and/or the computer that can figure out what is going on are available.

The problem as I see it is to try to classify the impact of failure upon the aircraft motion.



BASIC PROBLEMS

- ASSUMPTIONS
  - ONE (OR MORE) AERODYNAMIC OR PROPULSION CONTROL ELEMENT FAILS OR IS SERIOUSLY MALFUNCTIONING.
  - SENSORS AND COMPUTERS ARE WORKING.
- PROBLEMS
  - CLASSIFY THE IMPACT OF FAILURE UPON AIRCRAFT MOTION
    - STATIC (EQUILIBRIUM)
    - DYNAMIC
  - ISOLATE FAILED ELEMENT
  - QUANTIFY FAILURE IMPACT
  - CHANGE CONTROL STRATEGY
- RAPID FAILURE DETECTION, ISOLATION, IDENTIFICATION, AND QUANTIFICATION MAY BE CRITICAL.

I think there are two very distinct and different kinds of problems we have to address: (1) what is the impact of this control element failure upon the static or equilibrium flight of the airplane, and (2) what may be the impact of that failure upon the dynamics of the airplane?

Quite often, of course, there will be failures that you cannot classify using this very neat distinction; but, I think that it is important to at least try to put the problem in some kind of a box so we can talk about it. Obviously we should try to isolate the failed element and quantify its impact; then somehow, we have to change the control strategy. Whether we do that by developing proper displays for the pilot or whether this is done automatically raises another set of very fascinating issues.

However, time is critical in all of these applications and our ability to rapidly identify that a failure has occurred, isolate it, identify it to the degree possible, and, in particular, quantify its impact, may be critical.

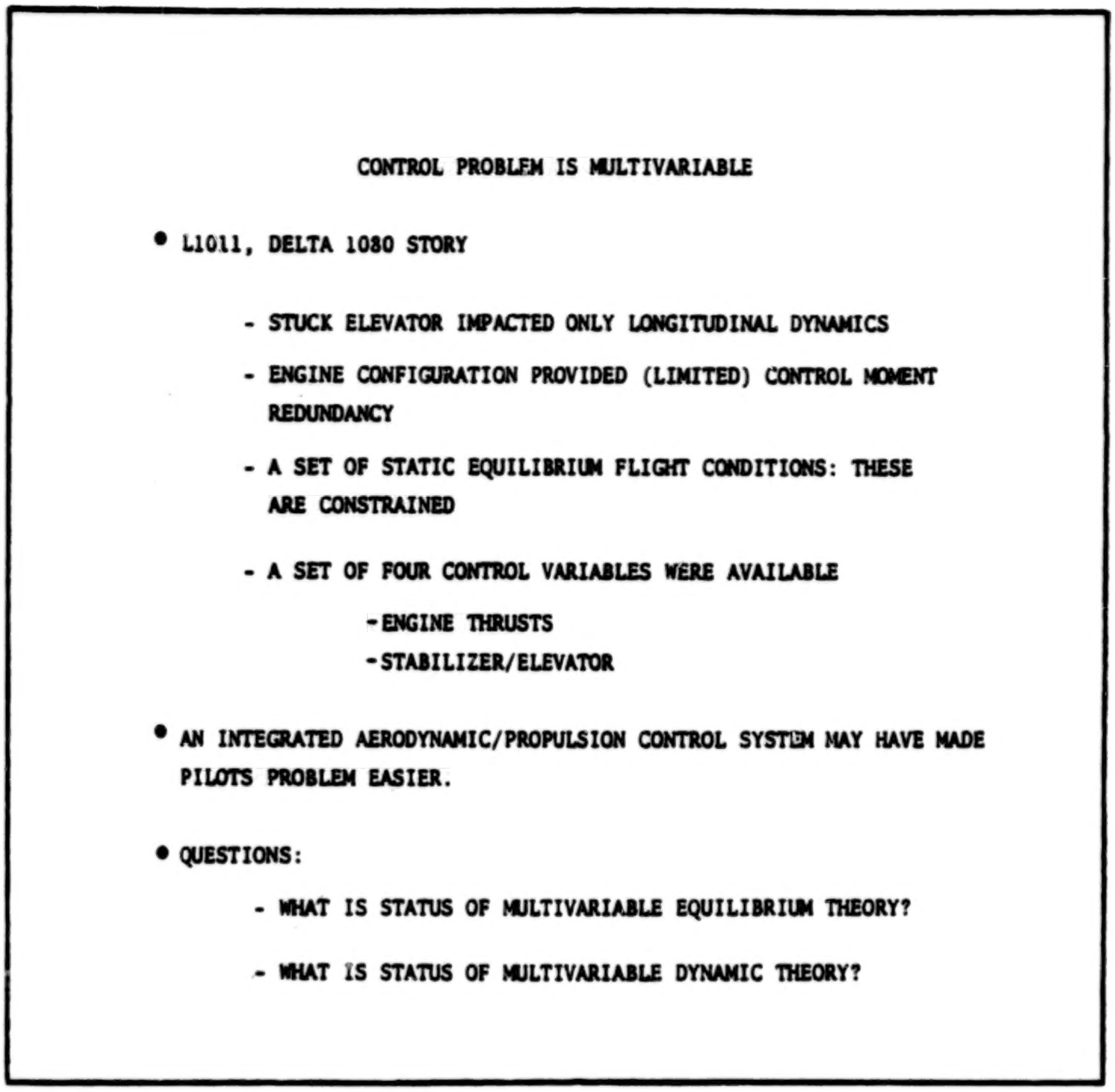
PRESENTATION THEME

- OVERVIEW AVAILABLE RESULTS IN STOCHASTIC CONTROL THEORY THAT ARE RELEVANT TO RESTRUCTURABLE CONTROL PROBLEM FOR AIRCRAFT

Given the names of the people that are making presentations, I decided to take a particular theme for this talk. I will present an overview of some available results in stochastic control theory because that is the discipline that this problem falls under.

First of all we are talking about control. The fact that it is also stochastic control is obvious because we certainly cannot anticipate the failure. I would like to stress that most of the results that I am going to talk about have not yet appeared in the literature; some have appeared as Ph.D. theses recently completed at MIT. I will try to overview them, and include some other research that is going on at ALPHATECH in order to pull this presentation together.

This will give a bird's eye view of what is known from a theoretical point of view, not just an overall stochastic control theory overview, but theory that I believe is really relevant to the problem at hand. This is the theme of my presentation.



CONTROL PROBLEM IS MULTIVARIABLE

- L1011, DELTA 1080 STORY
  - STUCK ELEVATOR IMPACTED ONLY LONGITUDINAL DYNAMICS
  - ENGINE CONFIGURATION PROVIDED (LIMITED) CONTROL MOMENT REDUNDANCY
  - A SET OF STATIC EQUILIBRIUM FLIGHT CONDITIONS: THESE ARE CONSTRAINED
  - A SET OF FOUR CONTROL VARIABLES WERE AVAILABLE
    - ENGINE THRUSTS
    - STABILIZER/ELEVATOR
- AN INTEGRATED AERODYNAMIC/PROPULSION CONTROL SYSTEM MAY HAVE MADE PILOTS PROBLEM EASIER.
- QUESTIONS:
  - WHAT IS STATUS OF MULTIVARIABLE EQUILIBRIUM THEORY?
  - WHAT IS STATUS OF MULTIVARIABLE DYNAMIC THEORY?

What I would like to do now, given that we are trying to put the problem into perspective, is to assert certain conclusions by occasionally referring to the material that was provided to us.

First of all, the control problem is a multivariable control problem. Suppose we examine the Delta flight story after the pilots found out that the stuck elevator clearly impacted the longitudinal dynamics but they did not particularly have any problems with the lateral control system.

If the engines were not canted, as they are on the L-1011, I do not know what the pilot could have done about it (unless he drilled a hole on top of the airplane and put some sort of a flap out there). The canted engines provided some control moment type of a redundancy; effectively, the failure of the elevator changed the set of the static equilibrium flight conditions that were possible.

The L-1011 pilot was particularly smart to realize that he did have a functionally redundant control that he would be able to operate, not in the most efficient manner fuel-wise, but at least to stabilize his airplane and to have a limp-home capability.

If you think about it, there were really four control variables available to the pilot. He had three engine thrusts that were canted. If he had some additional problems with the lateral dynamics, he may have been able to apply differential thrust in the two engines and still maintain equilibrium flight. So, my assertion that all of these problems have to be investigated in a multivariable context is based on these considerations.

Now, if there was some sort of an integrated aerodynamics/propulsion control system, the pilot's problems may have been a little easier, although that is beside the point.

If you accept my assertion that in all these examples we are dealing with multivariable control problems, we can ask the following questions: (1) what do we know about multivariable equilibrium theory, and (2) what do we know about multivariable dynamic theory from the point of view of control system design and building of models?

One of the conclusions is that we cannot think in terms of single input-single output kinds of control loops. There are at least two inputs and I think, for future airplanes, there is no reason why there will not be even more redundancy.

FAILURE DETECTION/IDENTIFICATION PROBLEM IS A MULTI-HYPOTHESIS TESTING PROBLEM

- L1011, DELTA 1080 STORY
  - FLIGHT CREW HAD TO FORMULATE, TEST, AND REJECT SEVERAL HYPOTHESES, E.G.
    - . STABILIZER SETTING
    - . HYDRAULIC CHECKS
  - NO AVAILABLE SENSOR THAT COULD DIRECTLY IDENTIFY STUCK ELEVATOR.
- LESSONS:
  - FAILURE HYPOTHESES MAY HAVE TO BE ACCEPTED OR REJECTED VIA INDIRECT MEASUREMENTS.
- QUESTIONS:
  - WHAT IS THE STATUS OF HYPOTHESIS TESTING THEORIES?
  - GIVEN COMPUTATIONAL CONSIDERATIONS IN HYPOTHESIS-TESTING ALGORITHMS (COMPOUNDED COMBINATORIAL PROBLEMS), HOW DO WE PRUNE THE DEPTH AND BREADTH OF TREE OF HYPOTHESES?
    - . ARTIFICIAL INTELLIGENCE?

The problem of identifying and detecting a failure, looking at it from a mathematical point of view, falls in a time-honored class of problems that usually arise in the first course of communication theory. If you look in Van Trees' book you will find out that the first technical topic is static hypothesis testing. Usually this is the signal-in-noise detection problem. From a system theoretic point of view, a failure causes something else to happen resulting in a hypothesis testing problem. It becomes a multiple hypothesis testing problem because there are many things that can happen in an airplane and you must be able to sort out all of the possible kinds of failures.

It may be possible to identify a priori certain failure, like stuck elevators and stuck ailerons, but there may be other types of structural changes in the airplane that will allow some sort of a limp-home kind of capability if some algorithm or some pilot is smart enough to formulate the problem.

In the L-1011 incident, if we read the Wall Street Journal article and just follow the narrative of that story, the Captain and the flight crew had to formulate and reject several hypotheses. They rechecked the stabilizer setting, went through a whole series of hydraulic checks, and made several other checks. This is very typical of the kinds of multiple hypothesis testing.

An audience with aerodynamics background may not realize the tremendous amount of generic problems that are involved in the same kind of approach.

Both at MIT and ALPHATECH, we are very heavily involved in command and control types of problems and, in particular, intelligence problems. Take an intelligence analyst who has some vague notion that something is going on that is out of the ordinary in the Soviet Union. He must formulate a whole variety of hypotheses but he seldom confirms a hypothesis right at the start. We do not have the theory to prove that, but one is better off in rejecting all sorts of hypotheses and then going on and finding the correct one.

Another interesting thing is that many failures could be directly observed by a sensor if someone had the wisdom to monitor that particular control element. Quite often, if something goes wrong there is a little light that will illuminate to indicate a failure.

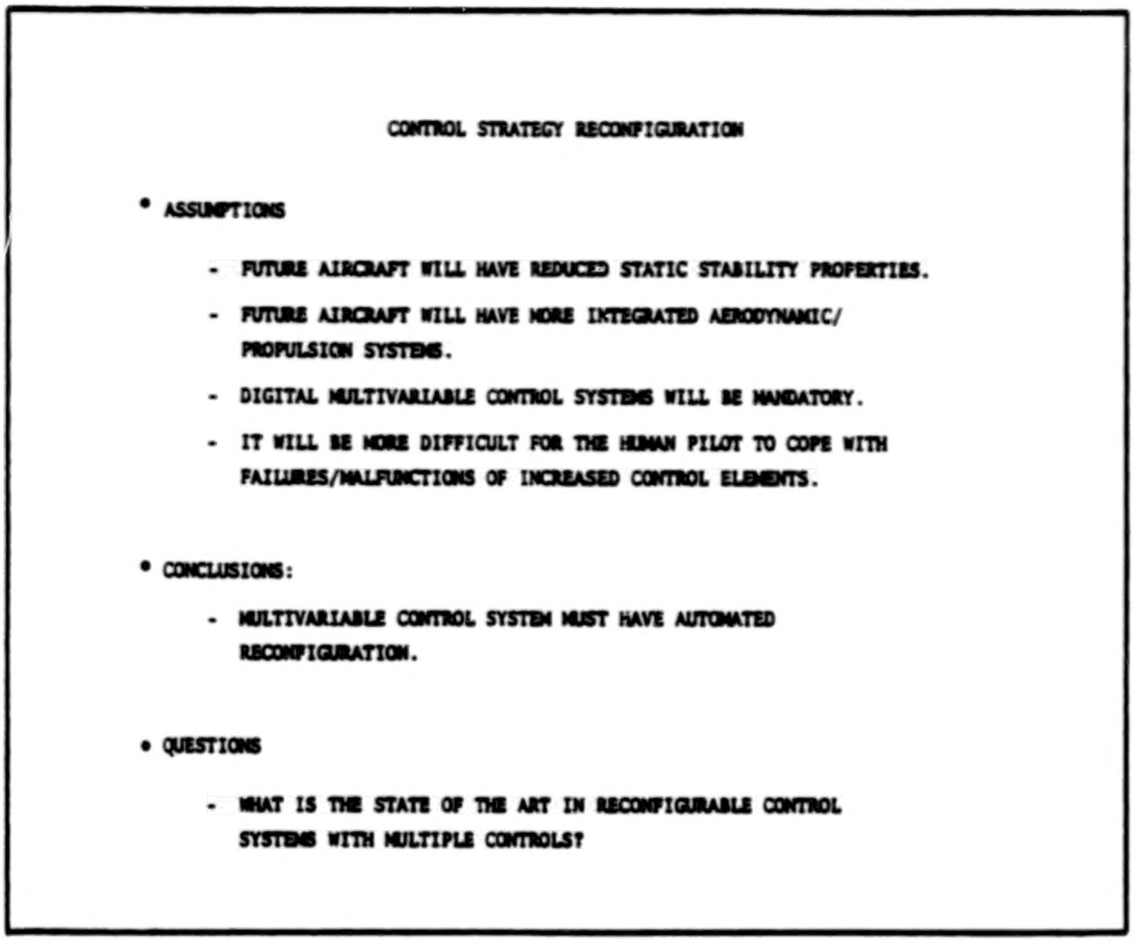
In the L-1011 case it did not happen. This leads to the class of hypothesis testing problems where a particular event that we shall call a hypothesis either has to be accepted or rejected. A direct measurement is not made, but must be inferred by either the static or dynamic interrelationship of several other variables that happen to be instrumented.

Given the fact, that we are dealing both with static and dynamic multiple hypothesis testing problems, then the natural question that arises is, "What is the status of hypothesis testing theories?" Actually, it is quite good, but it has never been applied, to my knowledge, with the possible exception of sensor failure detection problems in aerospace problems.

Whenever you do hypothesis testing, even if we have super-duper computers, there still exists a very severe compounded, combinatorial problem. One cannot possibly keep in the computer memory, no matter how large it is, all possible hypotheses. One has to implement a rational procedure to bound both the breadth and depth of the hypothesis testing tree.

Given the fact that we formulate several hypotheses and that we may have to wait a certain amount of time to reject certain hypotheses and perhaps formulate new ones, we are thus creating some sort of a growing hypothesis tree which has to be pruned. This is a function of the computational resources available.

There are some helpful tools that people in artificial intelligence (AI) are using, and that we have been using in work in estimation theory. Every AI problem is a clever formulation that eventually disintegrates into a tree searching algorithm with rules on which way to go to efficiently search that particular tree.



CONTROL STRATEGY RECONFIGURATION

- ASSUMPTIONS
  - FUTURE AIRCRAFT WILL HAVE REDUCED STATIC STABILITY PROPERTIES.
  - FUTURE AIRCRAFT WILL HAVE MORE INTEGRATED AERODYNAMIC/PROPULSION SYSTEMS.
  - DIGITAL MULTIVARIABLE CONTROL SYSTEMS WILL BE MANDATORY.
  - IT WILL BE MORE DIFFICULT FOR THE HUMAN PILOT TO COPE WITH FAILURES/MALFUNCTIONS OF INCREASED CONTROL ELEMENTS.
- CONCLUSIONS:
  - MULTIVARIABLE CONTROL SYSTEM MUST HAVE AUTOMATED RECONFIGURATION.
- QUESTIONS
  - WHAT IS THE STATE OF THE ART IN RECONFIGURABLE CONTROL SYSTEMS WITH MULTIPLE CONTROLS?

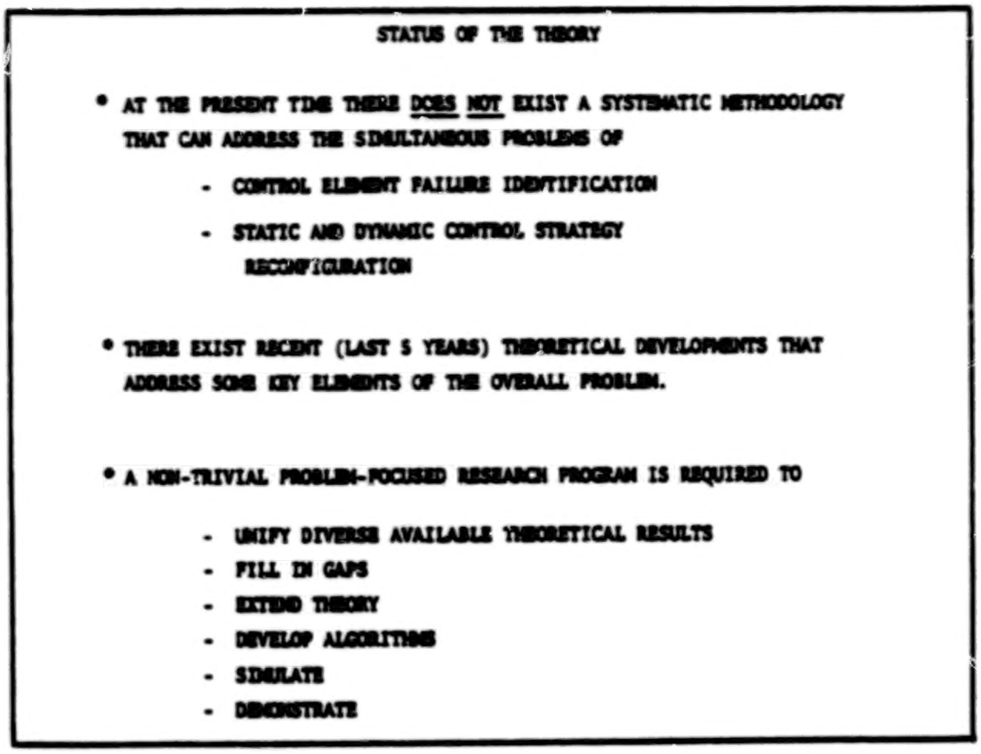
Let us now talk about the controls strategy reconfiguration. I am not talking about the control law. I am talking about the entire problem of designing the control compensator before you decide to change the control gains. There is a difference between changing the control strategy, the way to control a particular system, versus the details of specifying the numerical parameters associated with that control strategy.

If we make some reasonable assumptions that we are going to be dealing with increasingly unstable kinds of aircraft with reduced static stability and with integrated aerodynamic/propulsion kind of systems with too many things for the pilot to worry about, then we must have an automated, multivariable, digital fly-by-wire control systems.

The important thing is that it will be much more difficult for the human pilot to cope with the closed loop characteristics of his aircraft. This is a big distinction. In the problems that we have seen, the airplanes (DC-10, the L-1011), and most other commercial aircraft, the pilot could deduce something because he had just the open loop airplane to play with. It is a much harder problem if the pilot is stuck with both the open loop airplane and a digital control system. I think that this is a problem that we do not understand. How may a pilot be able to deduce that something is wrong and reconfigure a control strategy by some plan that incorporates the airplane with its failures together with the automated feedback control system?

I think this is a very big question and I do not believe that either NASA or the Air Force has addressed it at a basic enough level as yet to have a good understanding of it.

We have to think of multivariable control systems that have limited reconfiguration capabilities. At this point we can ask, what is the state of the art in reconfigurable kinds of control systems, not only single-input/single-output but also multiple controls, because there are many more degrees of freedom to adequately reconfigure control systems.



STATUS OF THE THEORY

- AT THE PRESENT TIME THERE DOES NOT EXIST A SYSTEMATIC METHODOLOGY THAT CAN ADDRESS THE SIMULTANEOUS PROBLEMS OF
  - CONTROL ELEMENT FAILURE IDENTIFICATION
  - STATIC AND DYNAMIC CONTROL STRATEGY RECONFIGURATION
- THERE EXIST RECENT (LAST 5 YEARS) THEORETICAL DEVELOPMENTS THAT ADDRESS SOME KEY ELEMENTS OF THE OVERALL PROBLEM.
- A NON-TRIVIAL PROBLEM-FOCUSED RESEARCH PROGRAM IS REQUIRED TO
  - UNIFY DIVERSE AVAILABLE THEORETICAL RESULTS
  - FILL IN GAPS
  - EXTEND THEORY
  - DEVELOP ALGORITHMS
  - SIMULATE
  - DEMONSTRATE

We have talked about the three main elements: multivariable type of static and dynamic systems, multiple static and dynamic hypothesis testing, and multivariable control systems reconfiguration. You might say, "Well Professor Athans, you are a theoretician and there are a few Ph.D. theses, full of equations that are incomprehensible, that we see from time to time--what then is the state of the theory?"

We do not have, right now, a systematic methodology, much less a theory, that can address the problems that one needs to have well understood, in order to attack this problem. It is not a kind of an application that you can say: "Well this is a problem; it is a multivariable control problem, and I can find the crossover frequency, and I can calculate its maximum crossover frequency and do other tricks." The control reconfiguration problem does not fall in an easily describable class of solved theoretical problems.

What we do have, again in the last five years, are theoretical developments that are somewhat pertinent to this problem. I think, as a first effort, we need some group that is familiar with these kinds of problems. Smart people have to devote significant time to a nontrivial but problem-focused research program to unify the diverse theoretical results, fill in gaps, extend the theory if necessary, develop algorithms, simulate and, of course, demonstrate.

TOPICS

- STATIC MULTIVARIABLE CONTROLS
  - CHANGES IN EQUILIBRIUM FLIGHT
- STATIC FAILURE HYPOTHESIS TESTING
  - IDENTIFY FAILURES THAT IMPACT EQUILIBRIUM FLIGHT
- DYNAMIC MULTIVARIABLE CONTROLS
  - STATUS OF LQG-BASED PLUS GAIN-SCHEDULING CONTROL DESIGNS
- FAULT-TOLERANT CONTROL THEORY
  - STOCHASTIC REGULATION OF LINEAR DYNAMIC SYSTEMS WITH CHANGING PARAMETERS
- DYNAMIC HYPOTHESIS TESTING
  - FAILURE IMPACT NOT DIRECTLY AND IMMEDIATELY SENSED
- GENERALIZED LIKELIHOOD RATIO (GLR) METHODS.
- ADAPTIVE CONTROL

I am now going to discuss in a little more detail the different topics listed in this viewgraph. We will be talking about static multivariable control problems that are associated with changes in equilibrium flight. We will talk about static failure hypothesis testing--things that you can sense as they impact the equilibrium flight of the airplane.

We can talk about dynamic multivariable controls such as how to design control systems. There is one and only one way to do multivariable control system design, and that is to use rational Linear Quadratic Gaussian (LQG)-based compensators with gain scheduling.

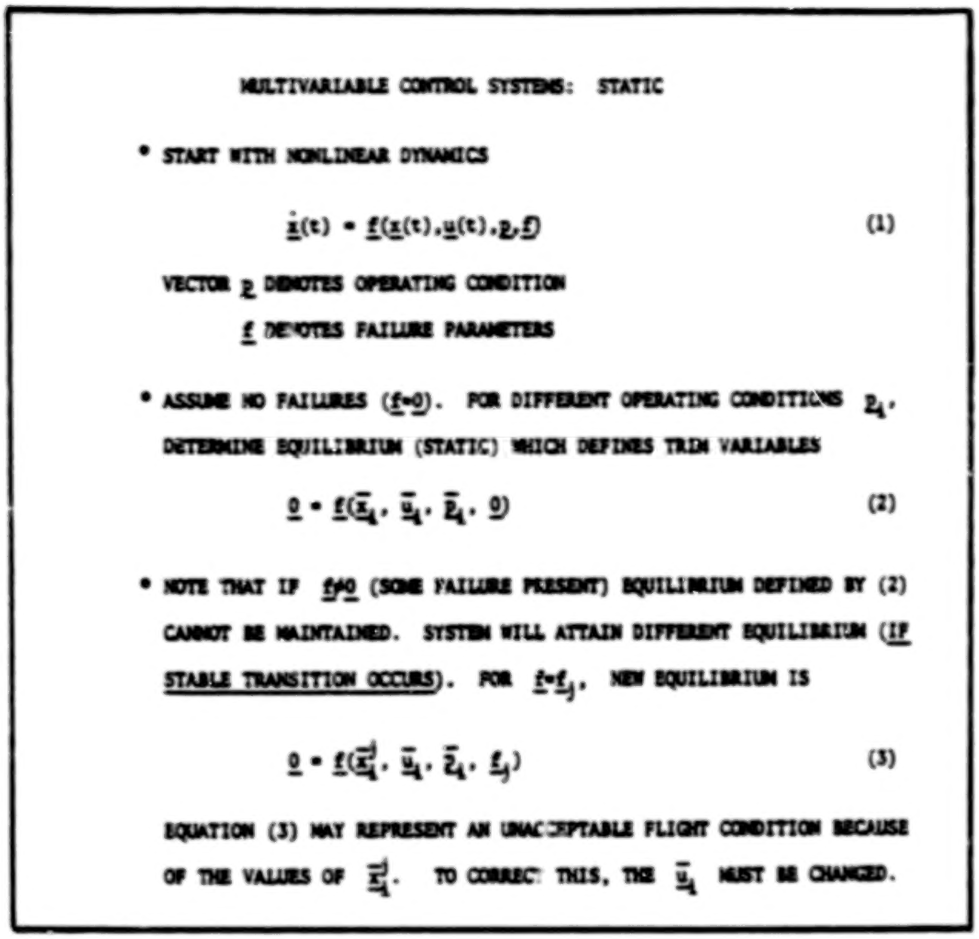
We can talk about fault tolerant control. Willsky, while at MIT, coined the term which I think he sort of borrowed from Draper's fault tolerant computing. Work that Willsky has been doing and also work that I have been doing to a certain extent for NASA Ames and NASA Langley the last couple of years is called fault tolerant control.

I am going to discuss some very specific available results that deal with the stochastic regulation of linear dynamic systems in which parameters change in a very real way. This is very interesting because it is the closest theoretical kind of a ball park that we have for analyzing the problem. We are also going to review dynamic hypothesis testing problems where the failure must propagate through a linear or nonlinear dynamic system and change the sensor output.

In all of these problems, very accurate models of the static and dynamic characteristics of the airplane must be available.

I am also going to say a few things about generalized likelihood ratio (GLR) methods that are intimately related to dynamic hypothesis testing methods.

The term adaptive control has been around since 1955. An adaptive control somehow, either explicitly or implicitly, identifies the system on the fly and simultaneously changes its control strategy and control gains to do the task. Finally, what is the status of adaptive controls? I would say that the control restructuring problem is a problem in adaptive control.



MULTIVARIABLE CONTROL SYSTEMS: STATIC

- START WITH NONLINEAR DYNAMICS

$$\dot{\underline{x}}(t) = \underline{f}(\underline{x}(t), \underline{u}(t), \underline{p}, \underline{f}) \qquad (1)$$

VECTOR $\underline{p}$ DENOTES OPERATING CONDITION
$\underline{f}$ DENOTES FAILURE PARAMETERS

- ASSUME NO FAILURES ($\underline{f}=\underline{0}$). FOR DIFFERENT OPERATING CONDITIONS $\underline{p}_i$, DETERMINE EQUILIBRIUM (STATIC) WHICH DEFINES TRIM VARIABLES

$$\underline{0} = \underline{f}(\bar{\underline{x}}_i, \bar{\underline{u}}_i, \bar{\underline{p}}_i, \underline{0}) \qquad (2)$$

- NOTE THAT IF $\underline{f} \neq \underline{0}$ (SOME FAILURE PRESENT) EQUILIBRIUM DEFINED BY (2) CANNOT BE MAINTAINED. SYSTEM WILL ATTAIN DIFFERENT EQUILIBRIUM (IF STABLE TRANSITION OCCURS). FOR $\underline{f}=\underline{f}_j$, NEW EQUILIBRIUM IS

$$\underline{0} = \underline{f}(\bar{\underline{x}}_i^j, \bar{\underline{u}}_i, \bar{\underline{p}}_i, \underline{f}_j) \qquad (3)$$

EQUATION (3) MAY REPRESENT AN UNACCEPTABLE FLIGHT CONDITION BECAUSE OF THE VALUES OF $\bar{\underline{x}}_i^j$. TO CORRECT THIS, THE $\bar{\underline{u}}_i$ MUST BE CHANGED.

I will show a few equations and try to illustrate certain kinds of concepts. Let us start with a dynamic multivariable control problem. Equation 1 is supposed to be a global, nonlinear description of an airplane where $\underline{x}(t)$ is the state variable vector. We are only talking about the rigid dynamics of the aircraft but with full nonlinearities. The symbol $\underline{u}(t)$ represents the vector of control variables that in an integrated propulsion system include, not only the aerodynamic surfaces, but things like nozzles, engine control variables, and engine geometry. The symbol $\underline{p}$ is a certain set of parameters that correspond to operating conditions. You can think of dynamic pressure as being one of the parameters but there may be more, especially if you have an integrated control system. There is another vector $\underline{f}$ that somehow captures the failures that we are talking about. Somehow a few of the important failures, perhaps not all sets of failures, have to be parameterized. This is only natural because an engine-out condition is a particular kind of failure that everyone knows is important, and pilots get drilled in their simulators to overcome that. If we build a theory we should be able to incorporate that type of failure.

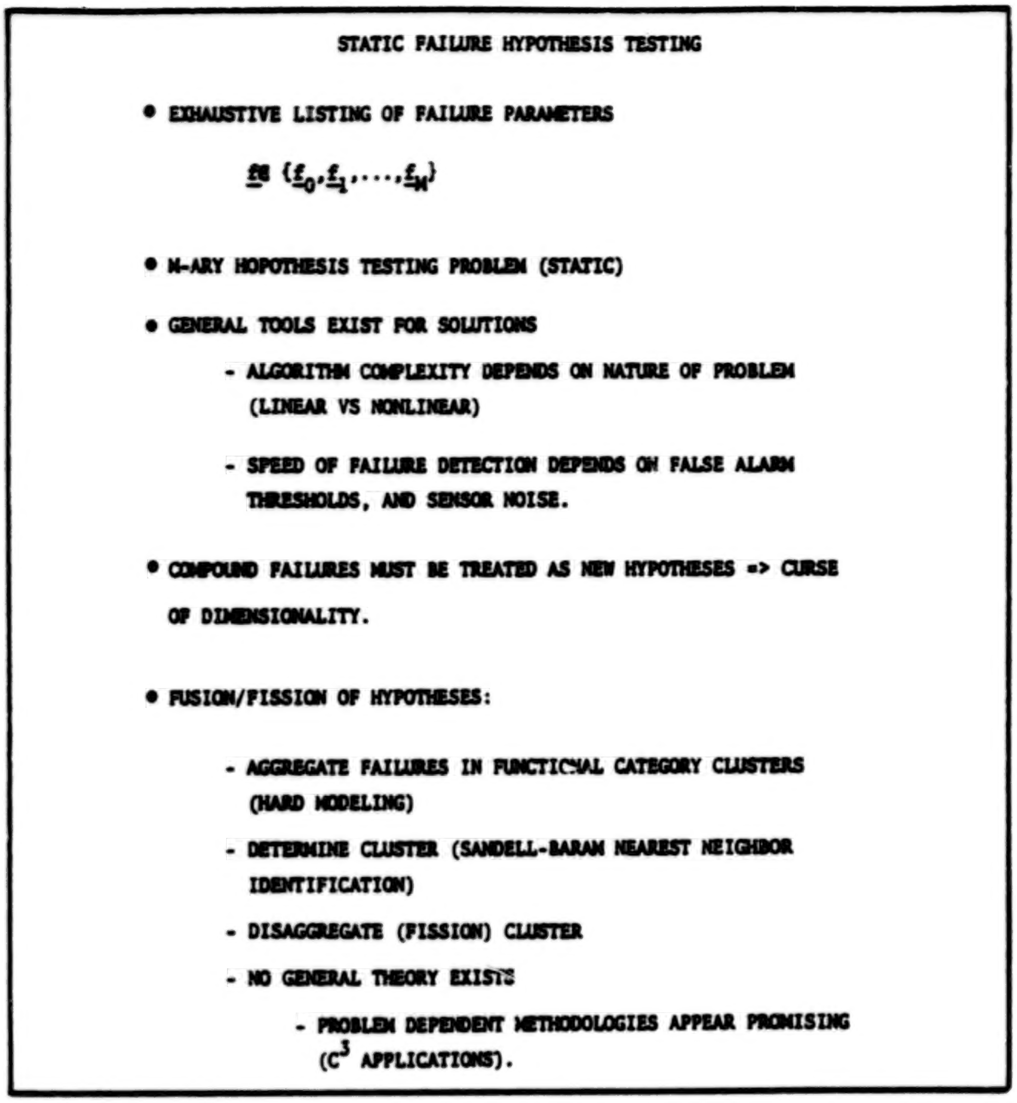
For normal equilibrium flight we assume that there are no failures ($\underline{f}$=0) and different operating condition vectors ($\underline{p}_i$) represent different dynamic pressure regimes. Effectively, it is this set of algebraic equations, given by Equation 2, that defines the set of equilibrium conditions and determine the trim state and control variables. We assume zero failures with the system at the particular operating condition. How do we trim the airplane? What are the results and the steady state values of the state variables? For example, what is the trimmed pitch angle, and the trimmed angle of attack?

Now, if we do have a failure shown by the vector $\underline{f} \neq \underline{0}$, then in general this specific equilibrium, (specific set of trim variables and specific steady state values of the state variables) cannot be obtained. Equation 2 cannot hold anymore unless you do not change your control variables, which is what Equation 3 attempts to illustrate. If the system is in the same operating condition when some failure appears, then the system is going to transition from a normal equilibrium condition to something else. That may be perfectly okay if the transition follows a stable trajectory. If the set of trim values of the state variables remain constant, in the transition from the equilibrium condition (Equation 2) to the equilibrium condition (Equation 3), and there is no change of static control strategy, the system may drift to something different. That may be good or it may be very bad, but that is how the aircraft is going to try to fly.

In the Delta story, at least for a while, the airplane attained an equilibrium condition that the pilot did not like, but it did not stall. In the DC-10 story, the plane went to a different equilibrium condition, that is, it started rolling to the left and went around and stalled. That is an equilibrium condition that is a no-no.

If the failure caused an unacceptable flight condition because of the new equilibrium values of the state variables, and this may be either benign or very dangerous, then effectively the only way to take the system out of this equilibrium condition and return to an equilibrium condition within an acceptable set is to retrim the airplane.

For many failures such as engine take-off failures, then you appropriately compensate for the loss of the thrust, the rudder, etc. These examples are the impacts of failures in a multivariable sense. The static equilibrium problem is in a mathematical framework that we can at least use to start with since we know a lot about trimming airplanes. However, I am not quite sure if we have really developed the knowledge, if you look at the true multivariable kind of an airplane where you have a variety of aerodynamic controls and propulsion controls, to generate the set of acceptable equilibrium conditions in an automated way. We must develop this knowledge to decide whether a failure puts the airplane in a set of equilibrium conditions that is tolerable. An inoperable condition will require some sort of restructuring and reconfiguration of at least the trim variables.



STATIC FAILURE HYPOTHESIS TESTING

- EXHAUSTIVE LISTING OF FAILURE PARAMETERS

  $\underline{f} \in \{\underline{f}_0, \underline{f}_1, \ldots, \underline{f}_M\}$

- M-ARY HOPOTHESIS TESTING PROBLEM (STATIC)
- GENERAL TOOLS EXIST FOR SOLUTIONS
  - ALGORITHM COMPLEXITY DEPENDS ON NATURE OF PROBLEM (LINEAR VS NONLINEAR)
  - SPEED OF FAILURE DETECTION DEPENDS ON FALSE ALARM THRESHOLDS, AND SENSOR NOISE.
- COMPOUND FAILURES MUST BE TREATED AS NEW HYPOTHESES => CURSE OF DIMENSIONALITY.
- FUSION/FISSION OF HYPOTHESES:
  - AGGREGATE FAILURES IN FUNCTIONAL CATEGORY CLUSTERS (HARD MODELING)
  - DETERMINE CLUSTER (SANDELL-BARAM NEAREST NEIGHBOR IDENTIFICATION)
  - DISAGGREGATE (FISSION) CLUSTER
  - NO GENERAL THEORY EXISTS
    - PROBLEM DEPENDENT METHODOLOGIES APPEAR PROMISING (C^3 APPLICATIONS).

The next slide deals with hypothesis testing. If we have some good models of the static airplane and the quantitative impact of the failures, then we may go on to another trim solution. We can also try to obtain the same autotrim in the dynamic sense by putting integrators in the right place in the control loops.

Suppose the failures are listed exhaustively which is a very difficult problem. From a mathematical point of view the problem of hypothesis testing, when you do not include the correct hypothesis, cannot be formulated or solved mathematically. You cannot say to the mathematics, "gee whiz, I forgot to input this hypothesis" -- put garbage in and get garbage out.

There are a lot of techniques, such as likelihood ratio techniques, at our disposal for solving hypothesis testing problems.

Let us suppose that we can exhaustively list the inputs for the failure parameters, then we have what is called the M-ary testing hypothesis problem in a static context. In general, tools are available for the solution. The complexity of the algorithms depends on the nature of the problem, whether the static problem is linear or nonlinear. The speed of the algorithm depends on thresholds that are intimately related to sensor noise as well as with the degree of confidence that you can assign to your mathematical model.

Notice that compound failures as in the DC-10 story have to be treated as additional hypotheses. Three things went wrong simultaneously. The pilot could have handled any one, or perhaps two, but not all three of them. In addition to loosing the engine, the slats were retracted, and there was asymmetry that the pilot did not know about. The asymmetry alarm of the slat system did not function and the stall warning system did not function.

If a bird hits us and sort of destroys a few things, the problem has to be treated as a compound failure. This generates additional hypotheses, and the only thing that limits our ability to do that is how clever we are at listing all the hypotheses where there are single failures or compounded failures, within the size and speed of our computer. We could never do everything we want.

These problems are not unique to airplanes, but arise in many places. It is the kind of problem that arises extensively in an area called multi-objective tracking in the surveillance problem for military command and control systems. Imagine some sort of airborne radar trying to keep track of all the ships in the ocean and presumably trying to figure out which ships are going straight and which ships are maneuvering. You may have false ships or new ships may appear, and quite often you do not know which return came from what object and this creates a lot of hypotheses. For this case, in order to handle the curse of dimensionality kind of a problem, people tend to apply fusion/fission types of hypotheses.

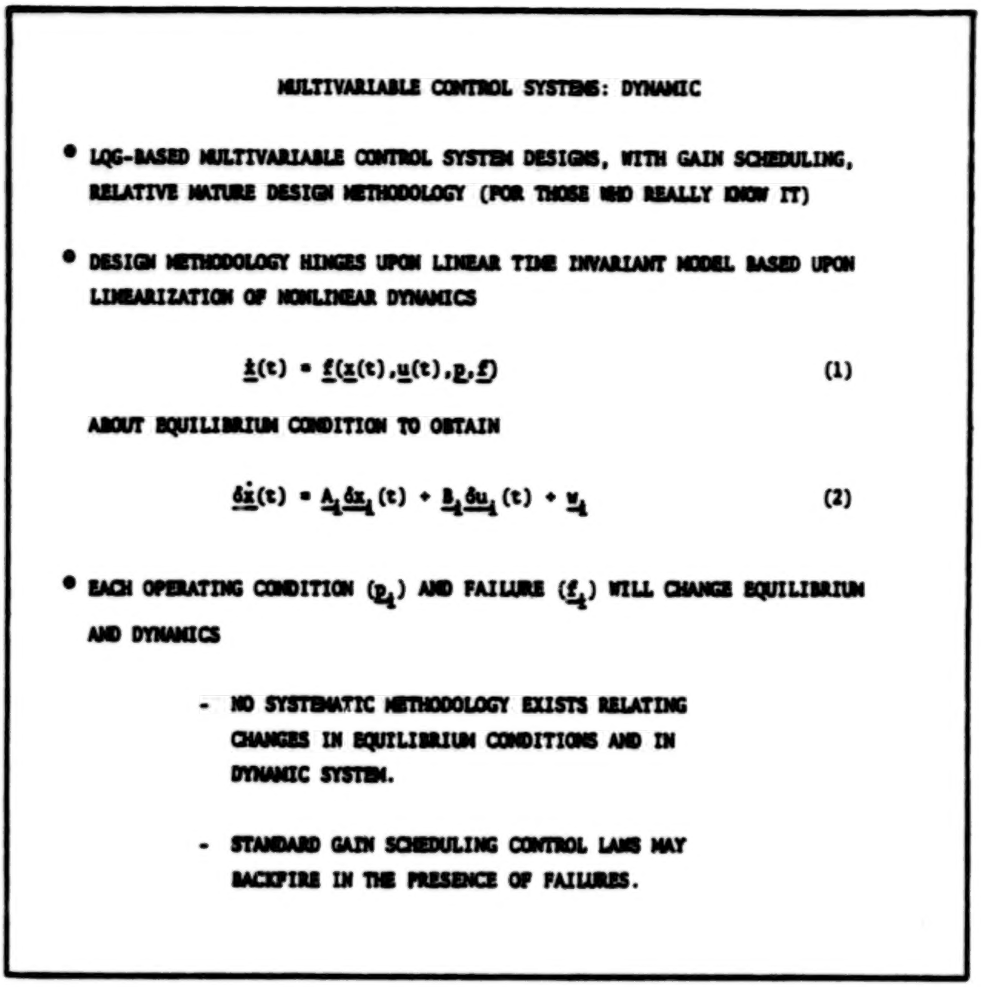
Effectively, the approach is to aggregate these hypotheses, which in our case will be failures, in certain functional category clusters. You can use things related to clustering theory in order to be able to tell the clusters apart. This approach involves modeling which is hard. You must know what you are doing, but in a sense it is possible.

I think from the point of view of the airplane, as in the Delta 1080 flight, if the airplane had an automated system, the first thing it should have indicated is a problem only in the longitudinal axis. Well, you may say that this is trivial since the pilot knows when the airplane is doing crazy things. But that is irrelevant. You must at least have the algorithms that are as smart as the pilot and hopefully smarter. Therefore, the fusion part of it is that you take a lot of hypotheses and you put them into clusters. The next step is to determine the correct cluster. In an aircraft you may say it is in the longitudinal dynamics. If you want to be more detailed, you may say that it will only effect the phugoid mode or the short period mode, or it is in the lateral dynamics. If there are many propulsion controls, you may say it is an aerodynamic control problem, a propulsion control problem, or it is a structural failure, or something else.

Although a cluster is not a detailed hypothesis, we know how certain classes of hypothesis testing algorithms will behave. They will converge to the nearest probabilistic model of the cluster. If you did a reasonable modeling job, the algorithm should work and the theory is available.

Once you find the cluster, which is like doing a tree search, and assume that it is on a specific branch of the tree, you do not have to search that part of the tree. We have mathematics that indicate that available algorithms will behave in a reasonable way if we did a decent modeling job.

Once you find the cluster you disaggregate and only deal with a small set of reasonable hypotheses in that cluster and forget all the other things. There is no general theory, but many techniques have been developed in other application areas. The conclusions are very much problem dependent.



MULTIVARIABLE CONTROL SYSTEMS: DYNAMIC

- LQG-BASED MULTIVARIABLE CONTROL SYSTEM DESIGNS, WITH GAIN SCHEDULING, RELATIVE MATURE DESIGN METHODOLOGY (FOR THOSE WHO REALLY KNOW IT)
- DESIGN METHODOLOGY HINGES UPON LINEAR TIME INVARIANT MODEL BASED UPON LINEARIZATION OF NONLINEAR DYNAMICS

$$\underline{\dot{x}}(t) = \underline{f}(\underline{x}(t),\underline{u}(t),\underline{p},\underline{f}) \qquad (1)$$

ABOUT EQUILIBRIUM CONDITION TO OBTAIN

$$\underline{\delta\dot{x}}(t) = \underline{A}_i\underline{\delta x}_i(t) + \underline{B}_i\underline{\delta u}_i(t) + \underline{w}_i \qquad (2)$$

- EACH OPERATING CONDITION ($\underline{p}_i$) AND FAILURE ($\underline{f}_i$) WILL CHANGE EQUILIBRIUM AND DYNAMICS
  - NO SYSTEMATIC METHODOLOGY EXISTS RELATING CHANGES IN EQUILIBRIUM CONDITIONS AND IN DYNAMIC SYSTEM.
  - STANDARD GAIN SCHEDULING CONTROL LAWS MAY BACKFIRE IN THE PRESENCE OF FAILURES.

We discussed some of the problems relating to changes in the static equilibrium and some of the approaches, namely static hypothesis testing. Let us go on to some of the dynamic issues postulating that the aircraft is going to require some multivariable dynamic control system both in the absence of failures and obviously in the presence of failures.

What is the status of the theory? I made the blanket statement that for those who really know how to use the LQG theory, combined with common sense gain scheduling, that it is a relatively mature design methodology. There are not many problems on that as long as we can trust that we have reasonable linear time invariant models. Furthermore, we know how to put these linear time invariant models in a global context through some gain-scheduling algorithm.

Now, how did this design methodology come up? We will start again with the nonlinear global equations of motion, as I have written them before, when we were talking about the static problems. First linearize about the particular equilibrium condition and, in the absence of a failure, get a set of linearized equations (2).

However, the thing that I would like to warn you about, is that there is a very intimate coupling between changes in operating conditions and/or "failures" on the one hand and system dynamics and equilibrium on the other hand. The important thing is that both changes in operating conditions and the occurrence of certain failures are going to change both the plant equilibrium and the dynamics. Clearly actuator-related failures or control element failures are going to change the $\underline{B}_i$ matrix.

In control theory we sort of know how to deal with the static problem by itself, and we can do hypothesis testing for the dynamic problem and miraculously we can linearize it and get a set of reasonable models. We can do all sorts of things with that including failure detection, which I will address in the next viewgraph.

The thing that bugs me is that we do not have, at least to my satisfaction, a systematic methodology whereby we can deal, in a sense, with this global nonlinear problem. We know it is too complicated to deal with in a global manner. How do we integrate the static equilibrium kinds of acceptable conditions to changes in the dynamic model. I do not say that this is necessarily hard or that it may take ten years to develop, but I do not think that it is part of a good, overall, generalized methodology. We sort of hope that changes in equilibrium conditions do not affect the dynamics of the system for the classes of problems that we are talking about. I can see that certain actuator-related failures, like the stuck aileron, stuck elevator, or something like that, will certainly affect the control effectiveness. However, if the airplane loses part of the wing tip or part of the tail of the elevator or something like that, the $\underline{A}_i$ matrix is certainly going to change. I do not know how to routinely go back and forth from the nonlinear dynamics to static equilibrium to the linearized equilibrium dynamic models. This poses another set of problems that we usually do not think about because we are really not flying a lot of automated, multivariable aircraft.

It may very well happen that rather than disconnecting, we must restructure very rapidly the control system that made the airplane easy for the pilot to fly in the absence of failures. The conventional gain scheduling control law that is designed in the absence of failures may backfire in the presence of failures that are not necessarily catastrophic. We need some methodology to understand under what conditions this could happen. Now, to do that we have to understand more about gain scheduling laws, their nonlinear robustness properties and that kind of theory.

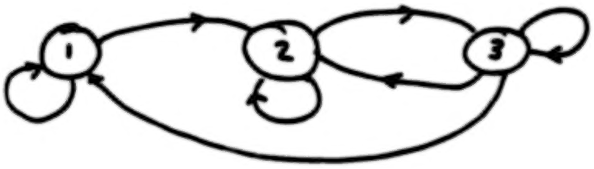
FAULT-TOLERANT CONTROL THEORY

- SOME THEORETICAL RESEARCH HAS BEEN DONE FOR LQG-TYPE OF CONTROL FOR LINEAR REGULATORS WITH ABRUPTLY CHANGING PARAMETERS.
- TYPICAL FORMAT: (ATHANS-BIRDWELL, WILLSKY-CHIZECK)

$$\underline{x}(t+1) = \underline{A}(\underline{\gamma}(t))\underline{x}(t) + B(\underline{\gamma}(t))\underline{u}(t) + \underline{\xi}(t) \qquad (1)$$

$$\underline{y}(t) = \underline{C}(\underline{\gamma}(t))\underline{x}(t) + \underline{\theta}(t) \qquad (2)$$

$\underline{\gamma}(t)$: DISCRETE PARAMETER VECTOR THAT "JUMPS" FROM ONE SET OF VALUES TO ANOTHER ACCORDING TO A MARKOVIAN CHAIN



QUADRATIC PERFORMANCE INDEX USED

- BOTTOM LINE:
  - VERY MESSY CONTROL RESTRUCTURING STRATEGIES (BANKS OF RICCATI EQUATIONS)
  - MINIMAL COMPUTATIONAL EXPERIENCE
  - THEORETICAL OVERKILL
  - UNREALISTIC ASSUMPTIONS

Let us now talk about the subject that Professor Willsky calls fault tolerant control theory. We have done some theoretical research in the last five years on LQG-type controllers with abruptly changing parameters. There were two Ph.D. theses: the first by Doug Birdwell, who is now at the University of Tennessee, and the second by Howard Chizeck who is now an assistant professor at Case Western Reserve.

There have been some additional kinds of research that is going on but I just want to give you a flavor for the kinds of problems and where our research is. We start with what looks like a standard linear system driven by white noise in discrete time and with a set of noisy sensor measurements. But now we make the problem more difficult by using a hybrid state space system which has a continuous state space for the normal state variables and a set of parameters, defined by vector $\underline{\gamma}(t)$, that is a set of discrete states. This vector can attain only a certain number of finite, discrete values and those are predictable in time and can jump from one value to another. The probabilistic evolution of $\underline{\gamma}(t)$ is described by a Markov chain. This certainly is what will happen if you have a failure. Something changes from one value to another at a random instant of time.

What we did, in a sense, is to combine the dynamics that describe the motion of the state as a function of time with a set of dynamics described by a Markov chain that sort of says that there is a probability at each instance of time that the parameter vector will go from state 1 and remain there or will jump to state 2. It can then stay in state 2 or jump to state 3. It can then stay in 3 or come back to state 2 with a certain probability or come back to state 1. In our mathematical model we can write all the transition probabilities. We have to control a system that really is nonlinear, but it only looks linear with a continuous state space and discrete state space. We assume that we cannot influence the transitions of these parameters. Obviously you cannot do that unless you get outside the airplane and fix the elevator to resume flight.

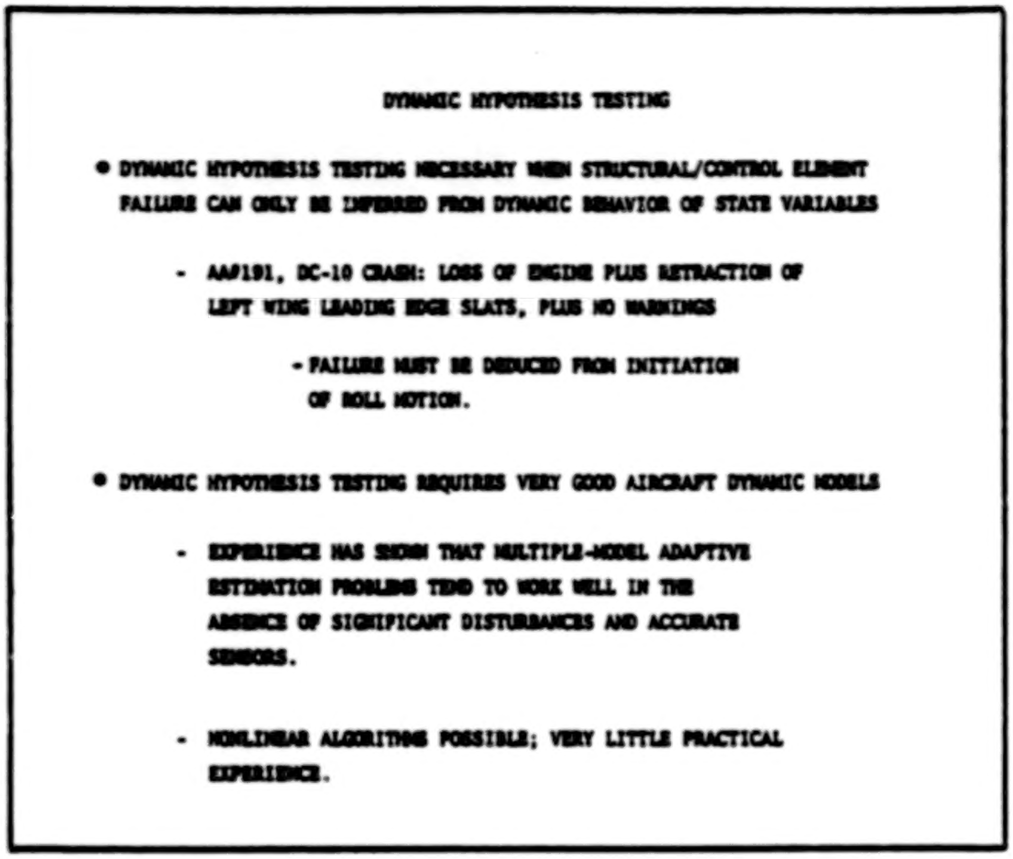
We have worked exhaustively using quadratic performance criteria on this class of problems. For anyone that tries to follow this kind of work I want to give some warning. The mathematics cannot stand too much uncertainty. If you formulate a stochastic dynamic optimization problem with uncertainty in the coefficients of the A,B,C matrices, and these stochastic uncertainties are due to jumps according to some Markov chain, then this is a multiplicative kind of uncertainty in the basic model. There is another uncertainty from the process white noise and a third uncertainty from the sensor noise. The mathematics quits if you try to incorporate all three sets of uncertainties. You get nowhere with dynamic programming and cannot solve the problem. If there is an optimum solution that can never be found, what good is it? What Birdwell's Ph.D. thesis showed was that we could not solve the problem with all three sources of uncertainty. We assume that we can measure the state variables which effectively says that the mathematics can deduce from the measurements of the state variables what the failure parameter is. There is a one step inherent time delay.

Pragmatically, you can tolerate a tiny bit of noise, and if you have just a slight turbulence, and you can measure the state variables, and if your failures were somewhat significant, you will pick them right up with one step-delay.

All of the approaches create some hedging strategies. There are some very messy restructuring strategies and we have not been able to analyze them over an infinite time interval to deduce global stability properties. Technically, you have to solve banks of Riccati equations that must be solved for linear systems off line but if we are going to do any actual restructure you may have to solve banks of Riccati equations in real time. I do not think that this is as horrendous a problem as it was, let us say, ten years ago.

In the problem at hand, we are saying that we start with a normal state and go to a failed state which will then induce another failure. That is the compounded failure problem. A full Markov chain may be a theoretical overkill, so we may want to specialize this approach to look at the classes of problems that we can reasonably expect. There are some unrealistic assumptions because we are assuming that we know the probabilities of failure.

I think that if we are really going to have a restructurable control law we cannot have just the aerodynamicist design the airplane. We have to make in a rational manner choices about what sensors we are going to use for the rigid body variables, how noisy they are, what failures specific sensors may measure directly and which failure we have to infer from the available sensors. We have to do a complete sensor selection tradeoff. And most people do not do that in standard applications.

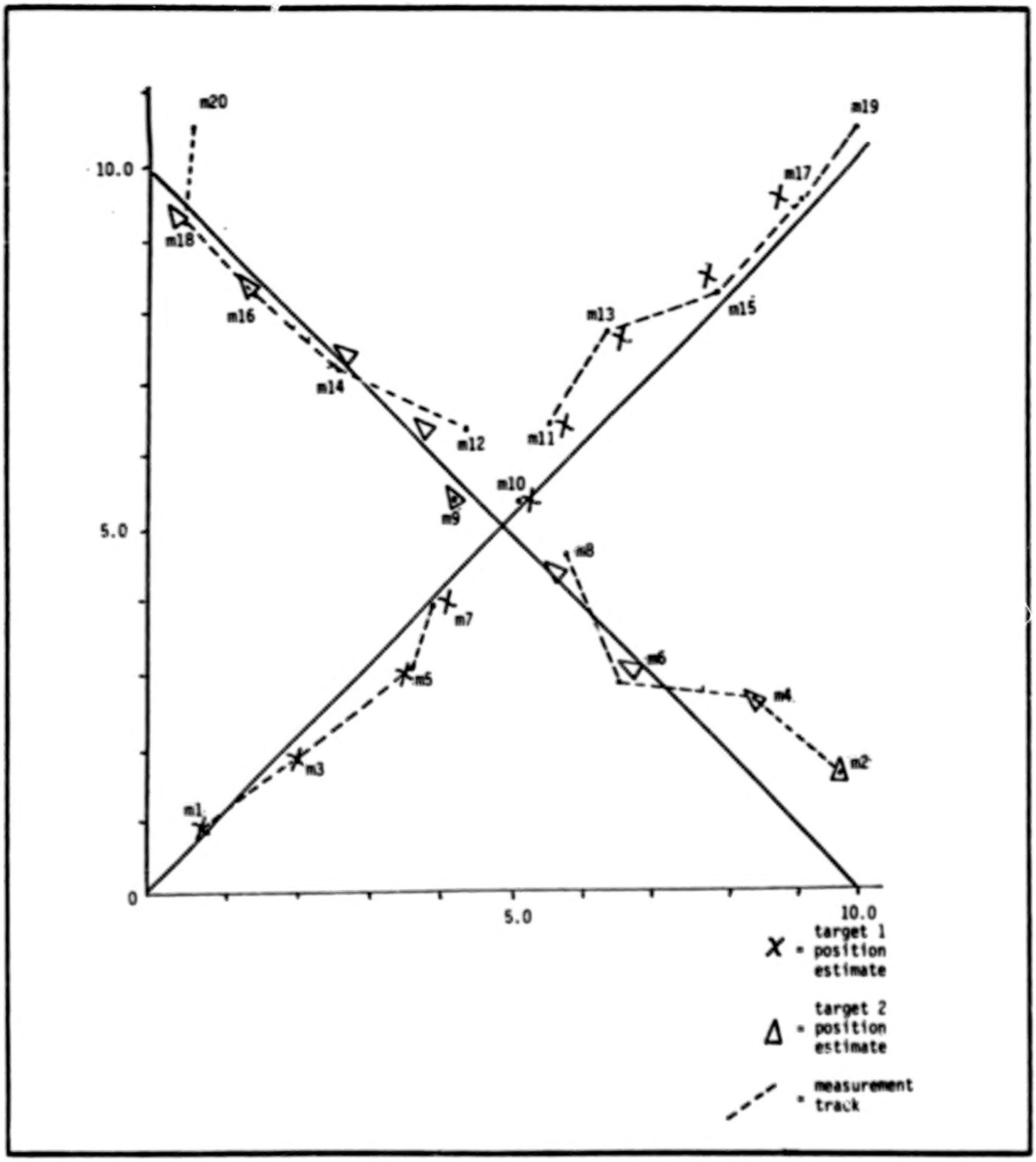


DYNAMIC HYPOTHESIS TESTING

- DYNAMIC HYPOTHESIS TESTING NECESSARY WHEN STRUCTURAL/CONTROL ELEMENT FAILURE CAN ONLY BE INFERRED FROM DYNAMIC BEHAVIOR OF STATE VARIABLES
  - AA#191, DC-10 CRASH: LOSS OF ENGINE PLUS RETRACTION OF LEFT WING LEADING EDGE SLATS, PLUS NO WARNINGS
    - FAILURE MUST BE DEDUCED FROM INITIATION OF ROLL MOTION.
- DYNAMIC HYPOTHESIS TESTING REQUIRES VERY GOOD AIRCRAFT DYNAMIC MODELS
  - EXPERIENCE HAS SHOWN THAT MULTIPLE-MODEL ADAPTIVE ESTIMATION PROBLEMS TEND TO WORK WELL IN THE ABSENCE OF SIGNIFICANT DISTURBANCES AND ACCURATE SENSORS.
  - NONLINEAR ALGORITHMS POSSIBLE; VERY LITTLE PRACTICAL EXPERIENCE.

The next topic is the dynamic hypothesis problems, which arise when the failure in the structural control element is not directly measureable, but has to be inferred through the dynamic behavior of the airplane. In the American Airline DC-10 crash, about the only way that the pilot could have figured out what was going on is to assume that the initial rolling to the left was not due to a wind gust or some disturbance like that, but that it was the initiation of some problem. You must have a system that is smart enough to indicate that. And it can only be inferred by measuring bank angle and other related variables.

Good dynamic hypothesis testing requires very good aircraft dynamic models. I want to stress that this is multiple model adaptive estimation and not closed loop control. The approach has worked very well in several kinds of applications that primarily use linear dynamics. Sol Gully may want to say a few things about this and the GLR experience that they had with nonlinear dynamics. There is not a lot of practical experience with nonlinear dynamics, but at least we have a place to start.



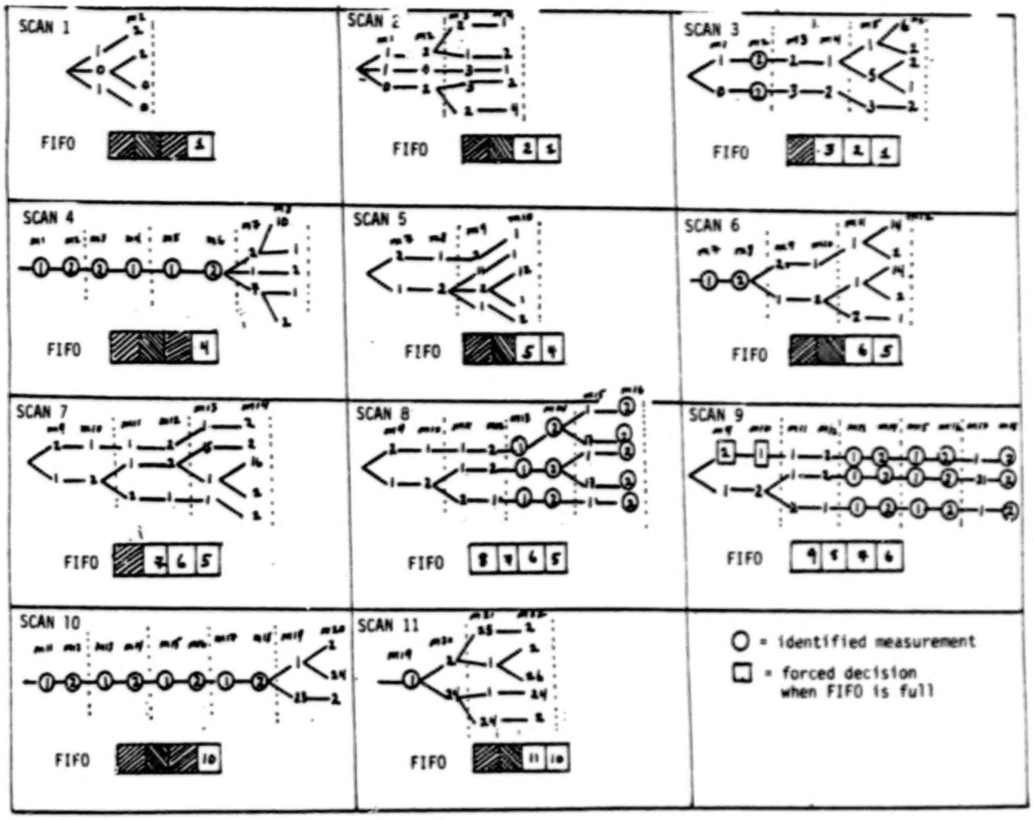
Let us take an example that has absolutely nothing to do with aircraft. This was a study supervised by Sandell. Let me tell you what the problem is to give you an idea how these hypotheses trees grow and compress, because something like that has to be implemented if you are going to solve the problem at hand.

This is a problem with two ships, both moving with the same velocity in straight lines as shown in the figure. You can observe the position of each ship in the presence of additive sensor noise, but you do not know which return came from which ship. However, you want to establish a complete track on the ship. Initially there is a lot of uncertainty as to the initial location of the ship. When the ships cross it is very difficult to determine the ship that returned the signal. The algorithm has to formulate this hypothesis.

In addition to the problem that you cannot match the radar return, there were two additional hypotheses: (1) that the return may be from a new ship that has not been included in the set of hypothesis which is how you sort of add new hypotheses, or (2) it may have been a false return.

In total, there are four kinds of hypotheses that are being carried around with the algorithm. Effectively you run a Kalman filter for each one of the combinations of hypotheses and that which builds up generates growing banks of Kalman filters. That is, in a sense, what the multiple model estimation algorithm asks.

Even for this problem, for something like ten data tracks, after ten sets of measurements, if you figure out how many possible hypotheses you will have, you will get something like 10^{36}, which is a pretty big number!


SCAN 1
FIFO
SCAN 2
FIFO
SCAN 3
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SCAN 4
FIFO
SCAN 5
FIFO
SCAN 6
FIFO
SCAN 7
FIFO
SCAN 8
FIFO
SCAN 9
FIFO
SCAN 10
FIFO
SCAN 11
FIFO
○ = identified measurement
☐ = forced decision when FIFO is full

A technique was developed and implemented by a fellow named Keverian to use finite buffer memories for that kind of a computation, and the algorithm he used was based on the artificial intelligence language LISP. LISP is really great for testing hypotheses, which is the reason it is the language of artificial intelligence people. Trying to write a Kalman filter in LISP was the major difficulty. The figure gives you an idea how the different measurements, there are sort of like eleven measurements and that is what scan means, add to the complexity of the problem. The boxes tell you how the memory is filling up, and if a box gets filled something drastic must be done to cut down the size of the tree. Otherwise it will keep growing.

I do not want to explain this graph but I do want to give you an idea of the kinds of problems that you are going to have if you really want a superior automated hypothesis testing algorithm for the airplane. You probably have more than the four slots shown in the figure, but something like this must happen. You start with some hypothesis and you begin to grow a tree. The tree grows in a particular way and some hypotheses get discarded. By the time of the third measurement, the buffer starts to fill up. Something drastic must be done. Choices are made and hypotheses are discarded from Scan 3 to Scan 4.

In Scans 8 and 9 you can see the ships are close together and that is the hardest part in telling them apart. You would expect to really fill up your hypothesis buffer and you are forced to make a decision. In Scan 9 the buffer is still full and all of sudden he gets the next measurements. The ships have now started moving away from each other and the new measurements collapse the hypotheses in Scan 10.

This process is really fascinating to watch in a computer. It requires certain computational tools that aerodynamic control theorists are not used to, but in many other disciplines these kinds of techniques are used day in and day out.

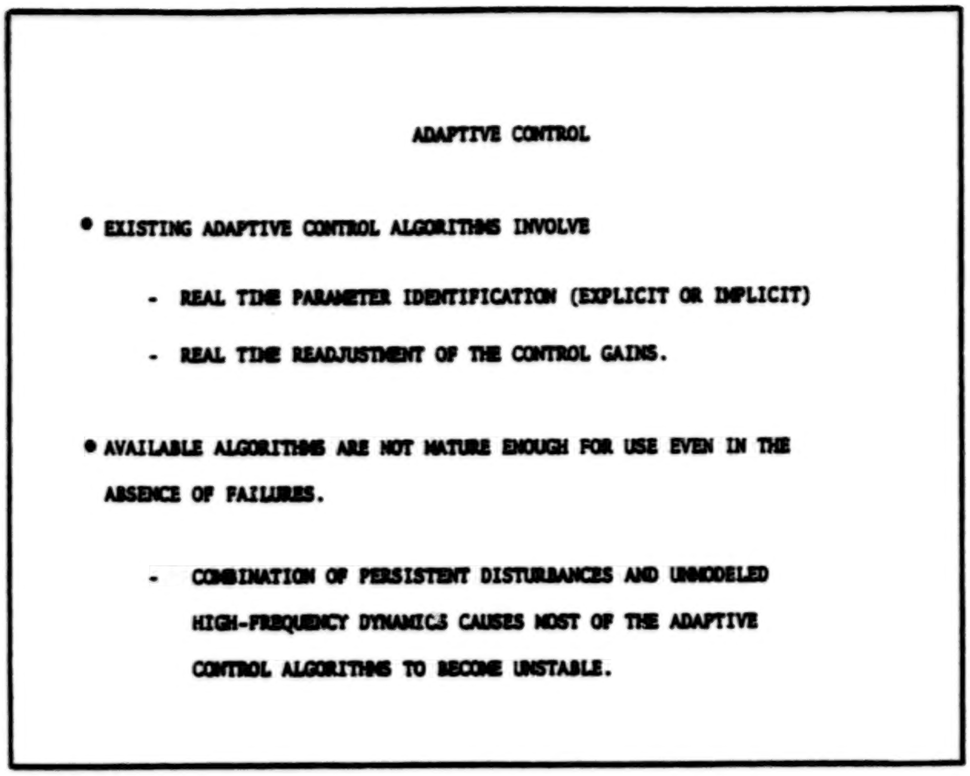
GENERALIZED LIKELIHOOD RATIO (GLR) METHODS

- THESE METHODS ARE SIMILAR TO DYNAMIC HYPOTHESIS TESTING ALGORITHMS, BUT THEY DIFFER IN ALGORITHMIC IMPLEMENTATION.
- LIMITED EXPERIENCE EXISTS ON THEIR PERFORMANCE
  - MOST GLR ALGORITHMS HAVE ASSUMED LINEAR DYNAMICS IN WHICH CONSEQUENCES OF FAILURE ARE MODELED AS ADDITIVE FORCING TERMS IN THE STATE AND SENSOR EQUATIONS (WILLSKY).

Generalized likelihood ratio (GLR) methods are very similar. They really are dynamic hypothesis testing algorithms, and are similar to multiple model estimation but with different algorithmic implementation.

A lot of people have experience with GLR. Many of the algorithms that I am familiar with assume linear dynamics and additive sensor noise, and the hypothesis impact was additive, biasing either the state equation or the sensor equation, either with steps or ramps.

Most of the computational experience that I have seen is based on Willsky's work, the work of his students, and also the work at Draper that was done on the F-8. From the point of view where the consequences of failure are modeled in a multiplicative way, which I think will happen in aircraft problems, I do not have any experience whether they will work very well or not.



ADAPTIVE CONTROL

- EXISTING ADAPTIVE CONTROL ALGORITHMS INVOLVE
  - REAL TIME PARAMETER IDENTIFICATION (EXPLICIT OR IMPLICIT)
  - REAL TIME READJUSTMENT OF THE CONTROL GAINS.
- AVAILABLE ALGORITHMS ARE NOT MATURE ENOUGH FOR USE EVEN IN THE ABSENCE OF FAILURES.
  - COMBINATION OF PERSISTENT DISTURBANCES AND UNMODELED HIGH-FREQUENCY DYNAMICS CAUSES MOST OF THE ADAPTIVE CONTROL ALGORITHMS TO BECOME UNSTABLE.

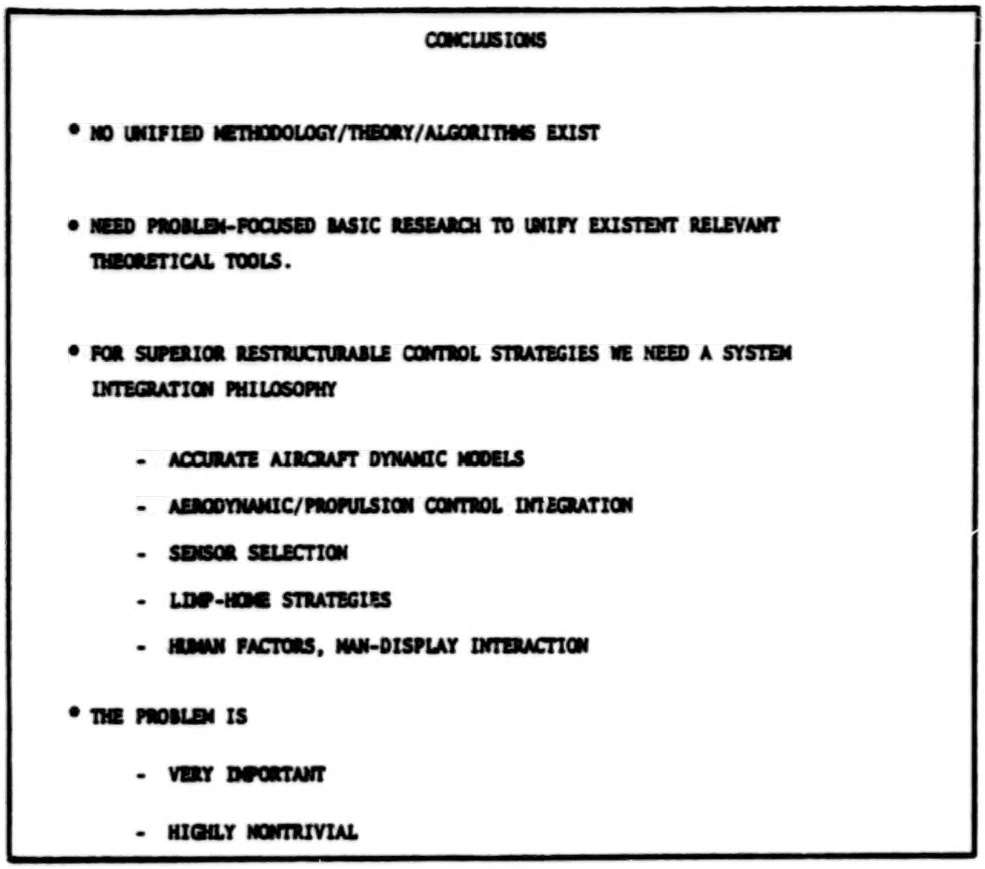
The last quasi-technical overview viewgraph is on adaptive control. We have, as Willsky calls it, a bazaar of adaptive control algorithms. These include model reference adaptive controls, self-tuning regulators, and new algorithms called dead-beat controllers developed by Ramadge, Goodwin, and Caines. In the last three years, several people including Dr. Valavani who works partly for Eli Gai at Draper and partly for me at MIT, have investigated the relationships among these algorithms.

In her thesis for Narendra, Dr. Valavani unified a lot of these algorithms. For linear, time invariant systems, there is real time parameter identification. It may be either an explicit least-squares kind of identification on the run, or some implicit identification as in the case of model reference techniques. There is also real time readjustment of the control gains.

Over two thousand papers have been written and a lot of excitement generated. You may have seen that people are giving courses to industry on how to make adaptive control practical. We have a recent MIT Ph.D. thesis [1] finished in November 1982 that Dr. Valavani and I supervised, which proved with a combination of analytical techniques and simulation results that all existing adaptive control algorithms are not worthwhile.

The algorithms may look excellent if you follow their theoretical assumptions, but in the presence of some persistent output disturbance and unmodeled high frequency dynamics all adaptive control algorithms considered become unstable with probability one.

The theory forces all of these algorithms, in order to do a good job for command following, to keep boosting up their loop gains and increase the bandwidth. Sooner or later, the large gain excites the inevitable unmodeled dynamics, which by definition cannot be modeled, and the adaptive system goes unstable. The statement that the available algorithms are not mature enough, even in the absence of failures, is quite an understatement.



CONCLUSIONS

- NO UNIFIED METHODOLOGY/THEORY/ALGORITHMS EXIST
- NEED PROBLEM-FOCUSED BASIC RESEARCH TO UNIFY EXISTENT RELEVANT THEORETICAL TOOLS.
- FOR SUPERIOR RESTRUCTURABLE CONTROL STRATEGIES WE NEED A SYSTEM INTEGRATION PHILOSOPHY
  - ACCURATE AIRCRAFT DYNAMIC MODELS
  - AERODYNAMIC/PROPULSION CONTROL INTEGRATION
  - SENSOR SELECTION
  - LIMP-HOME STRATEGIES
  - HUMAN FACTORS, MAN-DISPLAY INTERACTION
- THE PROBLEM IS
  - VERY IMPORTANT
  - HIGHLY NONTRIVIAL

What are my conclusions? No unified methodology / theory / algorithms exist that can just be put in a box and combined with an airplane. Again I repeat that I think we need a basic effort that will involve talents with more than just knowing aircraft dynamics, to unify the theory, especially in the unpublished literature. At the very least, we have to address the issues for accurate, nonlinear dynamic models. This is very important for dynamic hypothesis testing.

I talked about the problem of sensor selection before. We cannot put sensors on everything, since that is an overkill. Then you get into the problem that the sensors may fail which leads to sensor redundancy problems. We really need to develop some sensor selection strategies at the system engineering level. We have to decide if we want a computer to try to help the pilot, either by suggesting things to him or doing something automatically.

What do we mean by good limp home strategies? Also we should never forget the human factors in man-display interactions.

The control reconfiguration problem is very important and highly nontrivial, but I think it can be done by people who know what they are doing.

REFERENCE

1. Rohrs, Charles Edward: Adaptive Control in the Presence of Unmodeled Dynamics. Ph. D. Thesis, Massachusetts Institute of Technology, November 1982.

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ROBUST RECONFIGURATION FOR HIGH RELIABILITY AND SURVIVABILITY FOR ADVANCED AIRCRAFT

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Introductory Remarks

We have had some experience in the past with reconfigurable/restructurable controls. I guess the main message for today's talk is that there is bad news and there is good news. The bad news is that most of the emphasis in this area at Honeywell has been on military aircraft. However, we have had some experiences recently with what we might be looking at in the 1990's transport commercial aircraft. And we see a lot of trends that are very similar to experiences that we are going through or have gone through with military aircraft. To that end, the good news, therefore, is that I think a lot of things in the military carry over to civil aviation. I will try to point these out as I go along.

MOTIVATION

- RELIABILITY
- SURVIVABILITY

So given that, the title of my talk is Robust Reconfiguration for Higher Reliability and Survivability for Advanced Aircraft. The first thought was that survivability really does not have much to do with this. But I think that, as we get into it, we will find that the military's parallels with survivability also have an impact on what we are looking at here. Take the DC10 incident, for instance. This incident involved a dispersion problem in the hydraulics of the leading edge slats. They also had a problem as to which direction the slat failed. One of the issues in survivability of military aircraft, particularly the kill-given-hit survivability, is dispersion of things like hydraulics.

So as I mentioned, certainly the reliability aspects of the problem are part of the motivation, and in this case, survivability issues would also apply to commercial transports.

FCS RELIABILITY (Sensors, Computers, Actuators)

1. SENSORS

   - Proliferation of onboard strapdown sensors for FCS sharing
   - Standard RM proven on many systems
   - Analytical Redundancy is going into production systems
   - Robust reconfiguration feasibility demonstrated

2. COMPUTERS

   - Computer self test is S.-O.-A (~97%)
   - Fault tolerance ← gatelevel
   - Software V&V evolving but still a problem
   - Distributed arch. of cheap fault tolerant building blocks offer advantages

3. ACTUATORS - Clearly the Reliability Bottleneck

   - Analytical methods enhance actuator reliability
   - Localized processing feasible
   - Restructuring of FCS surfaces will have big payoff

I would like to, first of all, look at reliability as it is currently assessed, say in aircraft flight controls. This I think is basically common between the military and the commercial world. This is how we assess it at Honeywell, anyway. For military aircraft in particular and say the new 767 aircraft that Boeing is building, we are seeing a proliferation of onboard strapdown sensors that are available for flight control. I am going to discuss sensors very briefly and maybe touch on a couple of things in the computer area that might be of benefit to us and then go on to the actuator/surface problems.

Standard redundancy management has been proven on many systems with highly automatic flight control systems. Analytic redundancy, defined as the type of thing that has been developed mostly at Draper, is now going into production systems. One of the questions I am asked (I am sure Draper is too) is when is this stuff going to become real? It is real. It is here now and the technique has been proven in flight tests, and I know of at least one Honeywell system that is going into production. I believe it is being accepted.

Robust reconfiguration feasibility has been demonstrated, at least in the study arena through simulation, for advanced fighters. We have been able to show that you can take sensors in off-nominal positions and normalize them to the proper place to at least get some semblance of reasonable flight control.

Now let us discuss computers. Most of our emphasis in reconfigurability is going to end up in some sort of algorithm, i.e., we are going to create software. The question is do we have the hardware capability to implement that software. Many people say no. I think certainly the state of the art in computer throughput is coming around to being able to accept more advanced algorithms.

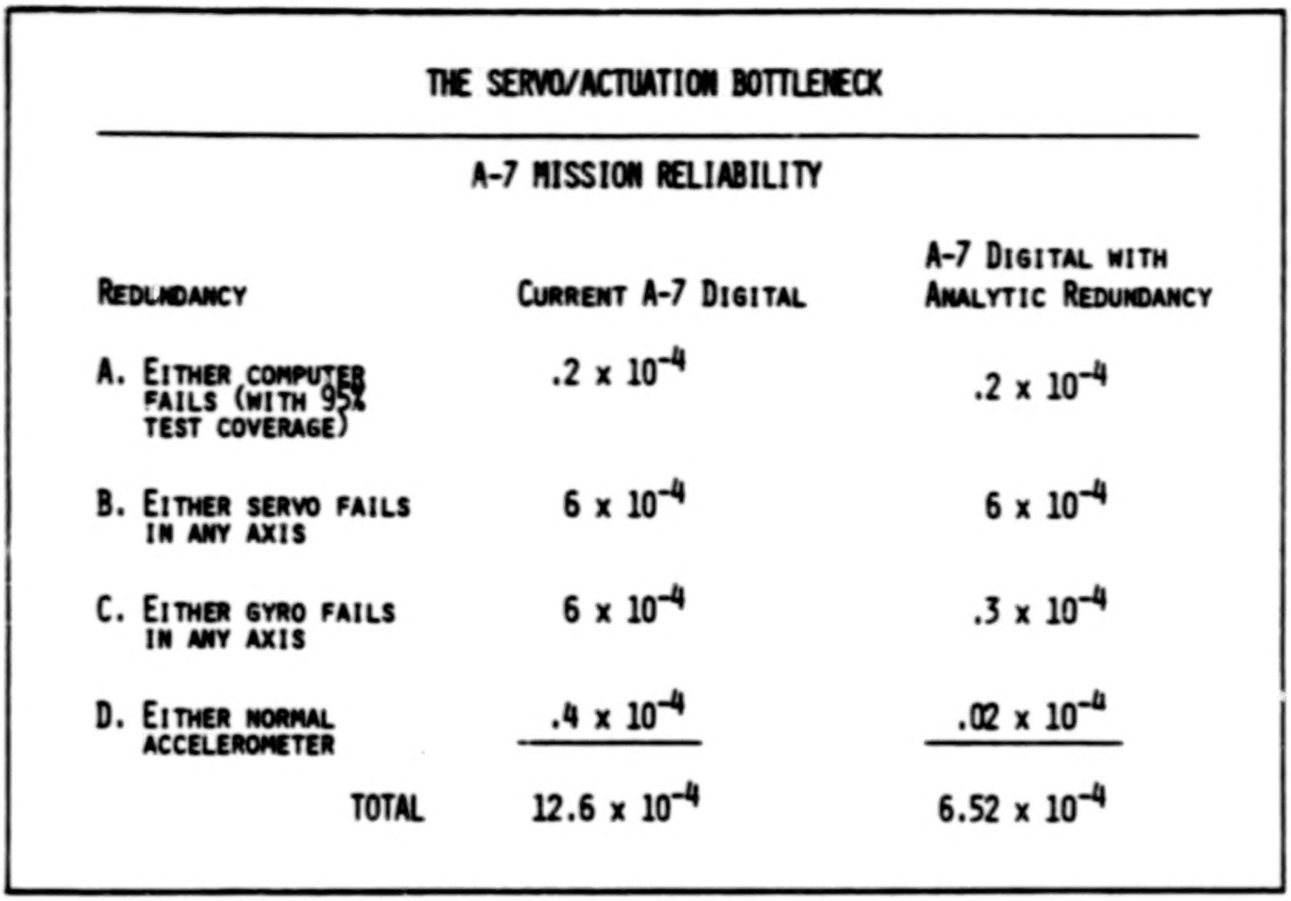
More software for reconfiguration, however, places an even heavier burden on computer fault tolerance than ever before. Computer self test is state of the art to about 97 percent and computer fault tolerance is rapidly improving. For instance, the new chip designs will have fault tolerance down to the gate level whereas the current day processors are fault tolerant basically at the box level in terms of self test.

We could talk about software validation and verification for hours. It is evolving but it is still a problem. It is going to be a problem for all of us who generate algorithms in particular.

Distributed architecture of cheap, fault tolerant building blocks offers advantages. A number of people are working on distributed architectures, and this could be dispersed architectures also. Things like computational elements at the actuator positions themselves offer nice ways of implementing a lot of fault tolerance, not only for the hardware itself, but actually for the actuator surface positions themselves. In one of the accidents that was discussed today (the L-1011) as Mike Athans pointed out, there was no sensor available. Well, there was no sensor on board the aircraft. In military aircraft and future commercial aircraft we are going to see a lot of LVDT's around the airplane. Now, unless that particular sensor itself fails, we should be able to detect, just from normal operation, particularly in a statically unstable vehicle, if a surface is not moving and perhaps if it is stuck in a very adverse position. This concept could be implemented in an actuator microprocessor.

Anyway, the notion of distributed architectures offers a great deal, and with it we can solve some of the environmental problems associated with computers. We will be seeing processing elements out in various spots along the aircraft, certainly around the actuator positions.

The current state of the art in flight control is such that the actuators themselves are the reliability problem. At SAAB in Sweden they are starting to look at that in some of the newer production aircraft. They will be using a kind of the equivalent to analytical redundancy in the actuator world. Some of the theoretical issues are actually a lot easier to deal with, but the impact, as we know, of a hardover actuator or a hardover surface is much more severe than a failed sensor. Localized processing is feasible, but I think that is related to the hardware issues. Restructuring of flight control surfaces can have a big payoff. If you compare surface redundancy management with sensor redundancy management, it is very unlikely that we will be adding surfaces onboard aircraft just for redundancy, particularly in military aircraft. I think that the same is true for highly augmented, future commercial transports. To add a surface just for redundancy would so effect the primary system performance that it might be unfeasible, whereas the sensors will proliferate. We are, however, adding surfaces for primary performance.



THE SERVO/ACTUATION BOTTLENECK

A-7 MISSION RELIABILITY

REDUNDANCY	CURRENT A-7 DIGITAL	A-7 DIGITAL WITH ANALYTIC REDUNDANCY
A. EITHER COMPUTER FAILS (WITH 95% TEST COVERAGE)	$.2 \times 10^{-4}$	$.2 \times 10^{-4}$
B. EITHER SERVO FAILS IN ANY AXIS	6×10^{-4}	6×10^{-4}
C. EITHER GYRO FAILS IN ANY AXIS	6×10^{-4}	$.3 \times 10^{-4}$
D. EITHER NORMAL ACCELEROMETER	$.4 \times 10^{-4}$	$.02 \times 10^{-4}$
TOTAL	12.6×10^{-4}	6.52×10^{-4}

The next viewgraph just shows basically a demonstration of the overall reliability bottleneck. Those of you who worked with the energy efficient transport of the IAAC program know that the overall failure, crucial failure reliability specifications on that is about 10^{-9}. This is a very difficult reliability specification to meet. The military has been dealing with stringent reliability specifications longer so in this particular case I have drawn some numbers from an old A-7 study that we did. For this study, a flight test of a set of dual computers that we had on board the aircraft pretty much solved the computer reliability problem as shown by these simple numbers. If you look at the other control elements such as the gyros, accelerometers, and servos, they all pretty much have the same reliability figures. However, we did some designs using analytical redundancy techniques and basically got reliability improvements for the gyro and normal accelerometer. Now the bottleneck becomes the servo area. That, certainly in terms of the military flight control technology, is the bottleneck.

FCS SURVIVABILITY ($P_{KILL/HIT}$)

- o SENSORS
  - DISPERSION NORMALIZATION FEASIBILITY DEMONSTRATED
  - RECONFIGURATION FEASIBILITY DEMONSTRATED
- o COMPUTERS
  - DISPERSION EASILY IMPLIMENTED WITH DISTRIBUTED PROCESSORS
  - COMPARTMENT ENVIRONMENTS NEED EXAMINATION
- o ACTUATORS
  - SURFACES FOR PRIMARY CONTROL FUNCTIONS PROLIFERATING-RSS, GLA, RIDE SMOOTHING, FMC, AND DIRECT FORCE MODES

    UTILIZE SURFACE RESTRUCTURING TO MAXIMIZE MISSION GOALS
  - ENGINE TECHNOLOGY ADVANCES
    - THRUST VECTORING
    - HIGH BANDWIDTH THRUST CONTROL

We have had some experiences with survivability which I think have some parallels to this issue that we are discussing today. Again, I first want to review where sensors and computers are before we get on to the actuator portion.

There has been some simulation demonstration of being able to reconfigure and configure flight controls based on normalization of dispersed sensors put in nonstandard positions. This has been examined by using navigation sensors for flight control where the NAV boxes essentially dictate where the sensors can be. So, as I mentioned, reconfiguration with dispersed sensors is possible. Computer dispersion is easily implemented with distributed processing.

Dispersion of elements in commercial flight control is also useful. The combination of failures, for instance, that occurred in the DC-10 disaster could have been avoided had we thought about dispersion a little bit more with certain key elements.

One of the key issues on computer dispersion is the environmental issue. Surfaces for primary control functions are proliferating in military aircraft. In the military, we are not too worried, at this point in time, about adding surfaces to auto-reconfigure out of a bad or impossible situation. We have an evolution that has occurred over the past 10 years where we now have a number of surfaces on board the aircraft that could conceivably reconfigure for a reasonable control of the aircraft. This could apply in commercial aviation if we go through the same trend of relaxing the static stability (RSS), implementing gust load alleviation (GLA), and perhaps some ride smoothing. Flutter mode control (FMC) is also being looked at in the commercial area. All of these add surfaces to the aircraft. I do not think we will see any direct force modes for the time being.

There are some other trends in technology that I think we can make use of here. Engine technology is now heavily going into the hardware end of thrust vectoring. The military is seriously examining this. Another new idea that is coming about is some capability with the engines to provide higher bandwidth thrust modulation. This would be important if we wanted yaw or roll control from differential engines. For commercial aircraft vs. military air craft, we are really just talking about a lower bandwidth, a lower set of frequencies that we are dealing with. I think the current state of the art in engine controllers is sufficient to have knowledgeable retrim, say if you have a hardover left or right stabilator or elevator. However, we are going to have to look at things like higher bandwidth thrust control to get any kind of additional yawing moment out of the system. And we see the engine people starting to evolve in that direction also.

PRELIMINARY SURVIVABILITY ISSUES

- FREE SURFACES REQUIRE
  - STABLE HINGE MOMENTS
  - SURFACE DAMPERS
- HYDRAULIC POWER DISTRIBUTION NEEDS IMPROVING
- HIERARCHY OF SURVIVABILITY

1. MISSION CONTINUATION	FULL MIL8785 SPECS
2. OPTIMUM RETURN TO BASE	LEVEL II FLYING QUALITIES
3. LANDING	LEVEL III FLYING QUALITIES
4. TRIM TO FLY	< LEVEL III FLYING QUALITIES
5. ENGINE OUT GLIDE	< LEVEL III WITH AUXILIARY POWER

The next chart shows some key preliminary issues. This first bullet emphasizes some things that I have heard this morning already. No amount of control theory, failure detection theory, etc., will be able to help you recover if you have a big surface that is hardover. In the case of a military aircraft, they mostly use the whole stabilator for pitch control. I think the L-1011 was fortunate in that they only use partial surfaces. A lot of research was done at the end of the Vietnam area on how to handle aircraft control problems once you have lost major surfaces or the use of major surfaces. One of the conclusions on a study of the F-4 was that if you had a hardover stabilator, there was nothing that you could do to recover. There are a couple of horror stories about what pilots did do to get out of situations like that.

One of the evolving techniques to handle a free surface now is to use surface dampers. The idea is that if you do have a free surface that has a stable hinge moment, if you do lose actuator power to that particular surface, you would insert a damper, or it automatically is inserted, into the system so that the surface does not flutter or cause a major difficulty.

Hydraulic power distribution, even in current military aircraft such as the F-16 and the YF-17, does need some improving from the survivability standpoint. I think the DC-10 experience has shown us that some different hydraulic power distribution could have helped out in that situation also.

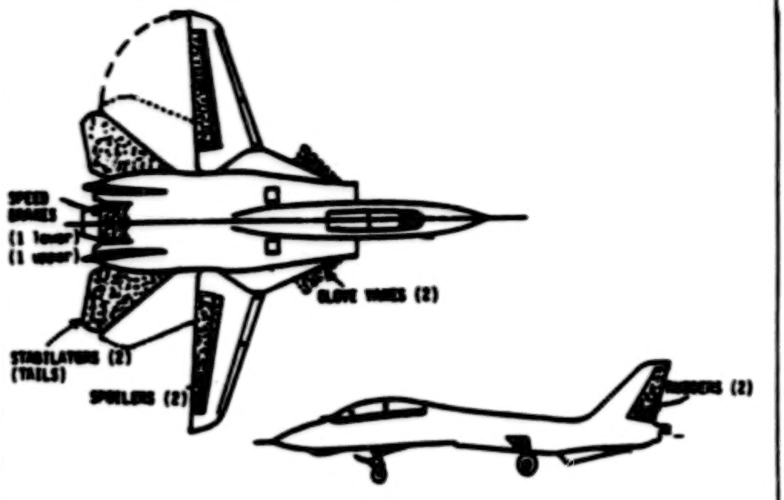
What is interesting here is the hierarchy of survivability for a military aircraft, which also can have some parallels. For instance, we looked at mission continuance in a MIL-SPEC sense. Mission continuance means that you have as much of the primary flight control capability as you originally had on the aircraft still available. The next notion is that of an optimal return to base, and here, of course, you are dealing with an enemy that keeps shooting at you or something like that. Landing requires some level III flying qualities under nice conditions. However, what is interesting here is that, if you are able to trim an airplane, you can get a lot of flying capability out of that vehicle, even though you do not have good flying qualities. I think the L-1011, for instance, was probably in this particular category. As you know, Los Angeles airport is susceptible to wind gusts on some days. If he had had gusty conditions out there on landing approach, he may not have made it. However, a combination of nice weather conditions and being able to recapture some semblance of flying qualities as he landed the aircraft allowed the pilot to save the aircraft. The fifth point [engine-out glide] maybe has no parallel here. It is of importance in the combat aircraft world.

SURFACE RECONFIGURATION DESIGNS

EXAMPLE 1 – GRUMMAN DISPERSED AND RECONFIGURABLE

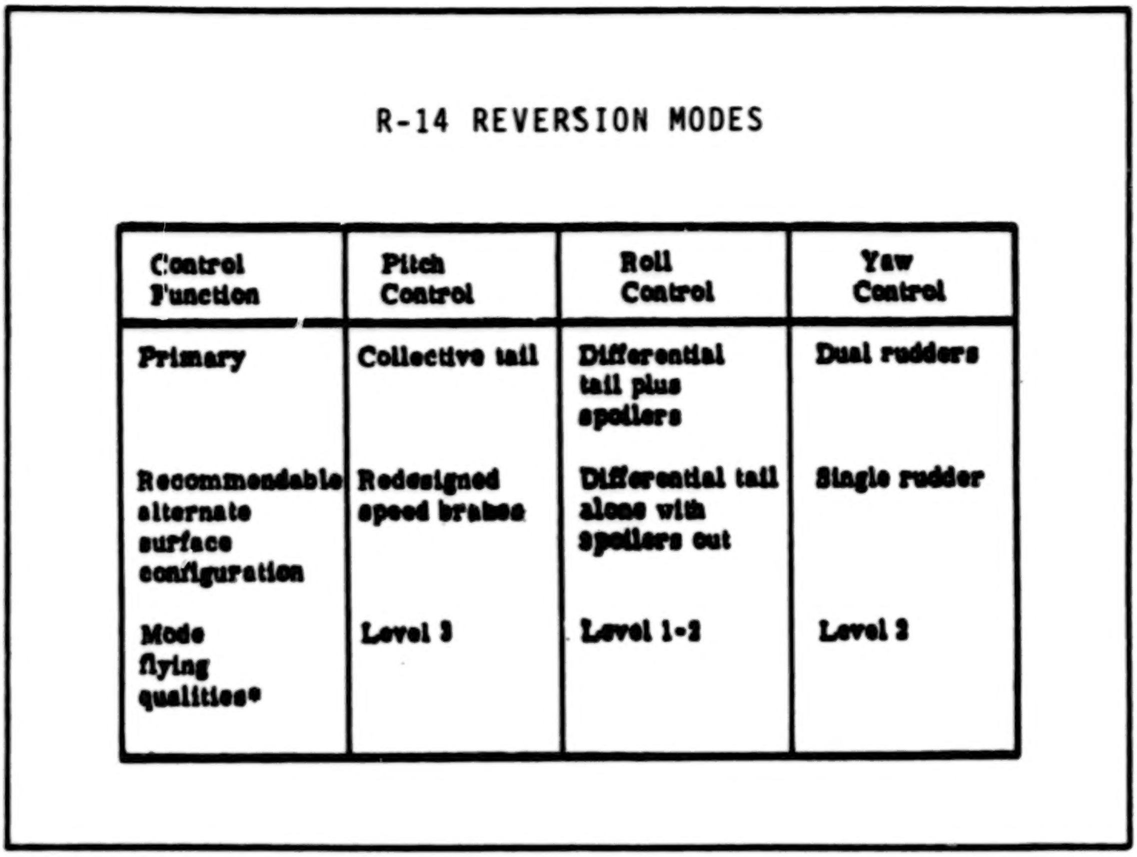
EXAMPLE 2 – HONEYWELL YF-16 REVERSION MODE STUDY

We have looked at surface reconfiguration and next I am going to talk about a couple of military fighters.


GRUMMAN STUDY VEHICLE

SPEED BRAKES
(1 lower)
(1 upper)
GLOVE VANES (2)
STABILATORS (2)
(TAILS)
SPOILERS (2)
RUDDERS (2)

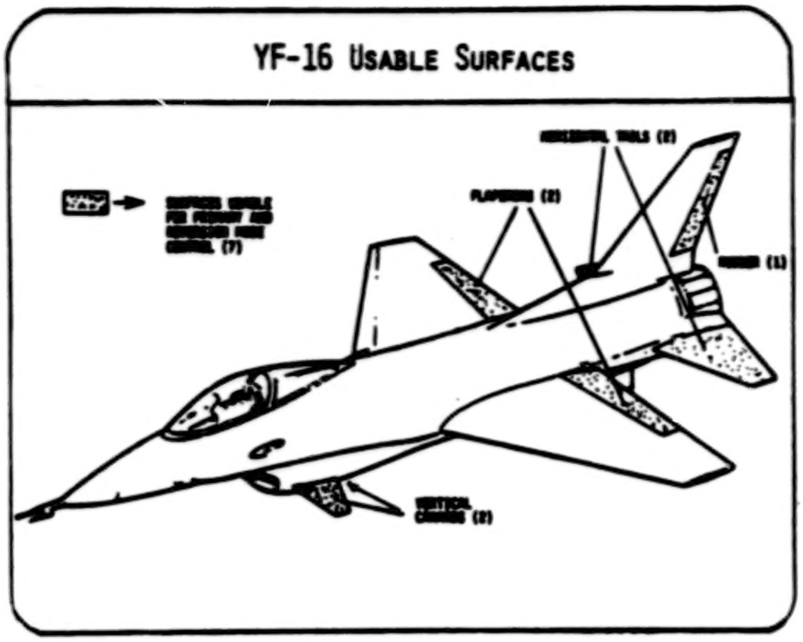
The first story is kind of interesting. It was actually done by Grumman on a statically unstable version of their F-14. This, by the way, has no parallel with the production F-14 aircraft. This is the basic setup of flight control surfaces available to a pilot, say in an F-14. His major pitch surfaces of course are two stabilators, independently actuated. Roll control is performed by combinations of spoilers and a rolling tail, achieved with differential deflections of the stabilators. He has a set of upper and lower speed brakes. He has glove vanes at his disposal although these quickly drop out as available sources for reconfiguration. Of course he also has twin rudders.



R-14 REVERSION MODES

Control Function	Pitch Control	Roll Control	Yaw Control
Primary	Collective tail	Differential tail plus spoilers	Dual rudders
Recommendable alternate surface configuration	Redesigned speed brakes	Differential tail alone with spoilers out	Single rudder
Mode flying qualities*	Level 3	Level 1-2	Level 2

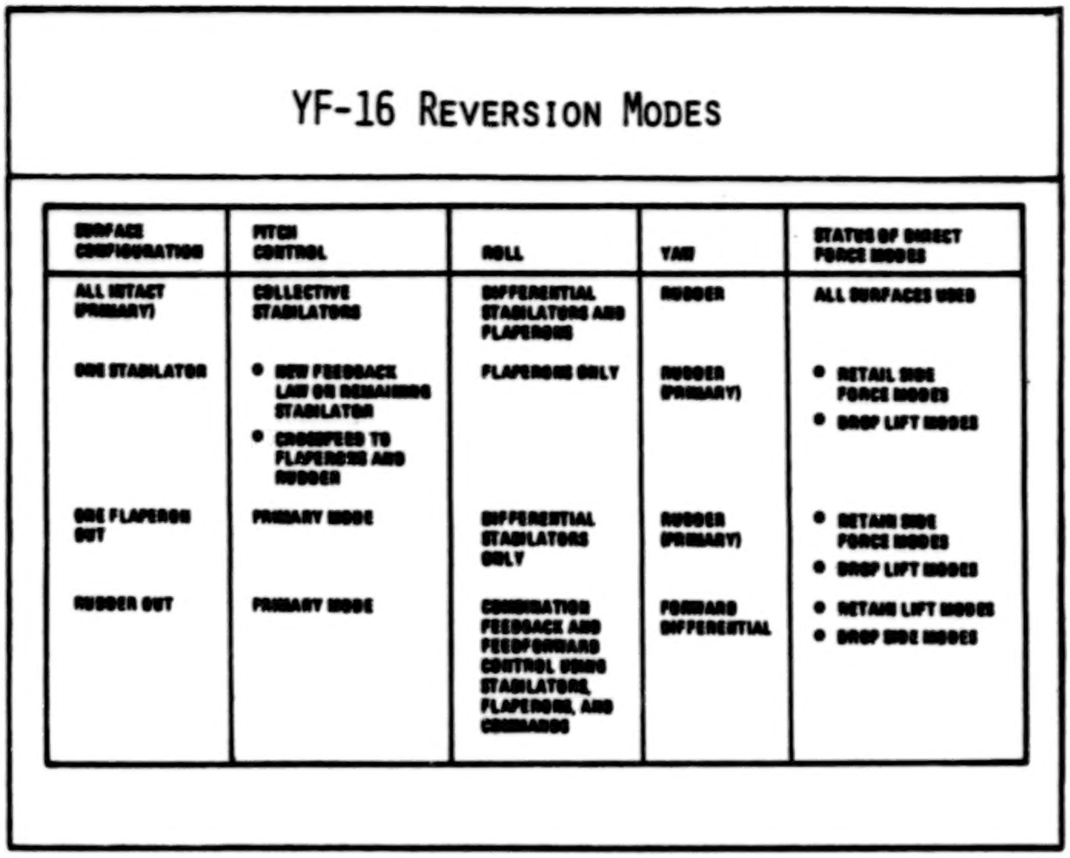
Here is what they found out when they looked at what would happen if they lost certain controls, and these are just single failure events. I have already mentioned the primary control surfaces. If, for instance, you lost pitch control due to one of the stabilators going out, then you have a mistrim in all axes. The recommendation was that, if you wanted to try and reconfigure for an event like this, you had to redesign the speed brakes because they did not have enough control authority as originally designed. In this particular case, controlling pitch with the remaining half of the stabilator would cause such a roll problem that spoilers alone did not have enough roll control power. So the idea was to try to get back to another pitch surface. Here the recommendation was that they redesign the aircraft with high bandwidth actuators, certainly on the speed brakes, and actually make the lower speed brake a little larger and they could achieve level III flying qualities in pitch. The message here is that there are some things that one can do in preliminary design of a vehicle that can offer some high payoff reversion modes.



YF-16 USABLE SURFACES

HORIZONTAL TAILS (2)
FLAPERONS (2)
RUDDER (1)
VERTICAL CANARDS (2)

Let us now look at the second example. Here we looked at the General Dynamics F-16 fighter. In the particular case of the YF-16 the data we used was for the CCV aircraft which has a vertical canard which can be used in the lateral directional axis. Here the primary control surfaces include the vertical canards, the flaperons, horizontal tails, and rudder.



YF-16 REVERSION MODES

SURFACE CONFIGURATION	PITCH CONTROL	ROLL	YAW	STATUS OF DIRECT FORCE MODES
ALL INTACT (PRIMARY)	COLLECTIVE STABILATORS	DIFFERENTIAL STABILATORS AND FLAPERONS	RUDDER	ALL SURFACES USED
ONE STABILATOR	• NEW FEEDBACK LAW ON REMAINING STABILATOR • CROSSFEED TO FLAPERONS AND RUDDER	FLAPERONS ONLY	RUDDER (PRIMARY)	• RETAIL SIDE FORCE MODES • DROP LIFT MODES
ONE FLAPERON OUT	PRIMARY MODE	DIFFERENTIAL STABILATORS ONLY	RUDDER (PRIMARY)	• RETAIN SIDE FORCE MODES • DROP LIFT MODES
RUDDER OUT	PRIMARY MODE	COMBINATION FEEDBACK AND FEEDFORWARD CONTROL USING STABILATORS, FLAPERONS, AND CANARDS	FORWARD DIFFERENTIAL	• RETAIN LIFT MODES • DROP SIDE MODES

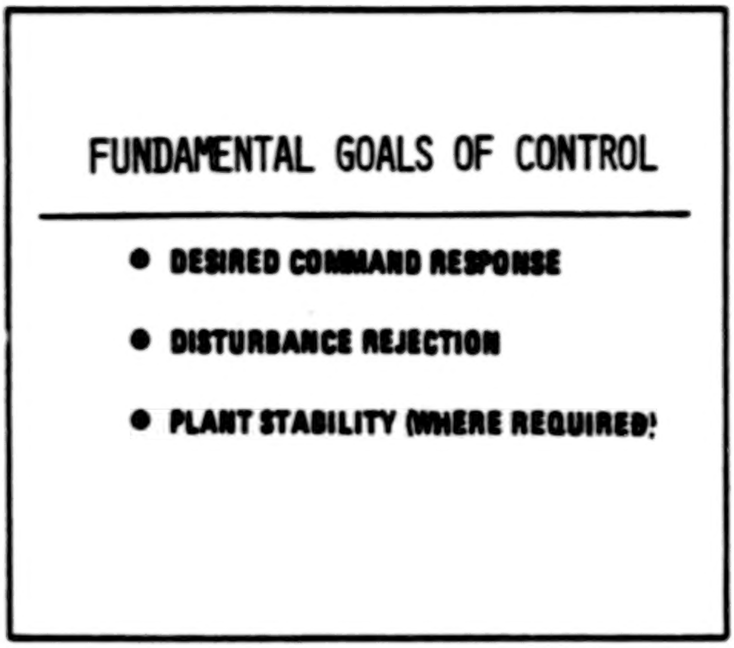
In this case, whether by design, we do not know, a lot of reconfigurability is possible. I will just skim over our results. First, we assumed that failed surfaces had stable hinge moments.

In all cases shown we were able to reconfigure on the remaining surfaces and get back to some level of good flying qualities just by reconfiguring on the other surfaces. For instance, if you only had one half stabilator, i.e., you lost the other half stabilator, you could use a new feedback control law on the remaining stabilator, use crossfeed to the flaperons and rudder, and achieve some semblance of flying quality for pitch control. You would still have the flaperons for roll control and you would have the rudder primary surface for yaw control.

In all cases, when you lose surfaces, you lose some performance. There is something that has to drop out. If you had no loss in performance due to a loss of surface, then you probably did not need all the surfaces in the first place. For this particular aircraft, they had some direct lift modes and they had some direct side force modes. They could retain some of the modes and had to drop the others. You can peruse the rest of these later on.

In summary, after the loss of a surface on an actuator on a surface, we could rationalize reconfiguring on the remaining surfaces.

Now, both aircraft discussed were statically unstable. I have talked to people at Boeing who tell me that there is a good possibility that the next commercial transport will be statically unstable also.

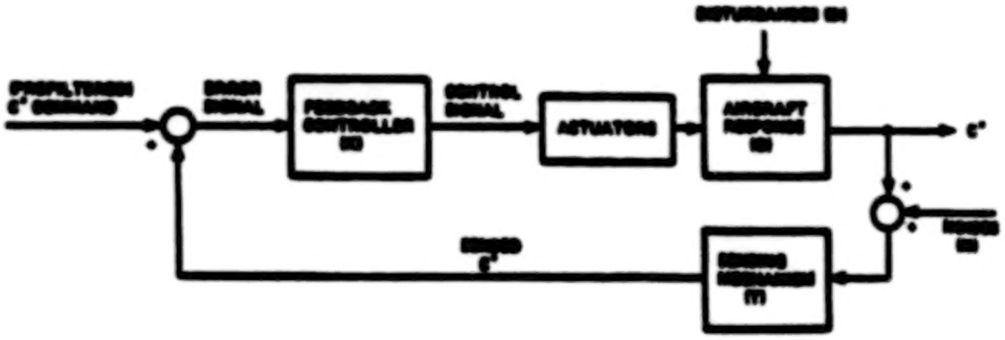


FUNDAMENTAL GOALS OF CONTROL

- DESIRED COMMAND RESPONSE
- DISTURBANCE REJECTION
- PLANT STABILITY (WHERE REQUIRED)

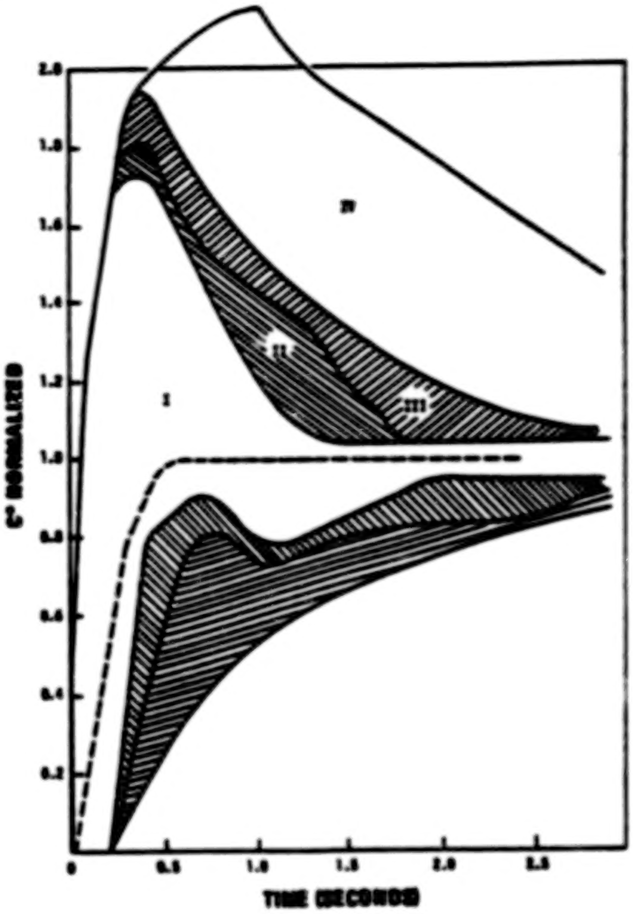
Next, I would like to quickly go through a design method that we use at Honeywell for designing control laws and then finish up with an attempt to show how we would bring that all together for a reconfigurable set of control systems for advanced aircraft. We have to start with the fundamentals. The fundamentals of control are, desired command response while looking at disturbance rejection and plant stability, where required. I certainly do not want to upset my stability with the control system design, but we are facing an era where, open loop, many airplanes in the future will be unstable and we have to worry about that particular issue.

C* FEEDBACK LOOP


DISTURBANCES (D)
PREFILTERED C* COMMAND
ERROR SIGNAL
FEEDBACK CONTROLLER (K)
CONTROL SIGNAL
ACTUATORS
AIRCRAFT RESPONSE (G)
C*
NOISE (N)
SENSED C*
SENSING MECHANISM (T)

We start with a classical control loop diagram. The diagram does not change even in the modern era. We have a plant which we will represent by G, a sensing mechanism, and a set of actuators that can be embedded in the plant. We have some sort of feedback control structure, and we have a feed forward command structure. Now, I have shown C* here. My military friends and flight controls colleague tell me that this is pretty passe now. You will forgive me, but I think for the purposes of our discussion this is not important. We have some error in the sensors represented by the noise. We have some disturbances going into the aircraft (wind gusts, etc.).

C* ENVELOPE



RIDE QUALITY: MIL-F-9490

$$D_I = \left\{ \int_{0.1}^{f_t} |W(f)|^2 \, |T_{CS}(f)|^2 \, \phi_g(f) \, df \right\}^{1/2}$$

WHERE

D_I = RIDE DISCOMFORT INDEX (VERTICAL OR LATERAL)

$W(f)$ = ACCELERATION WEIGHTING FUNCTION (VERTICAL OR LATERAL) 1/g

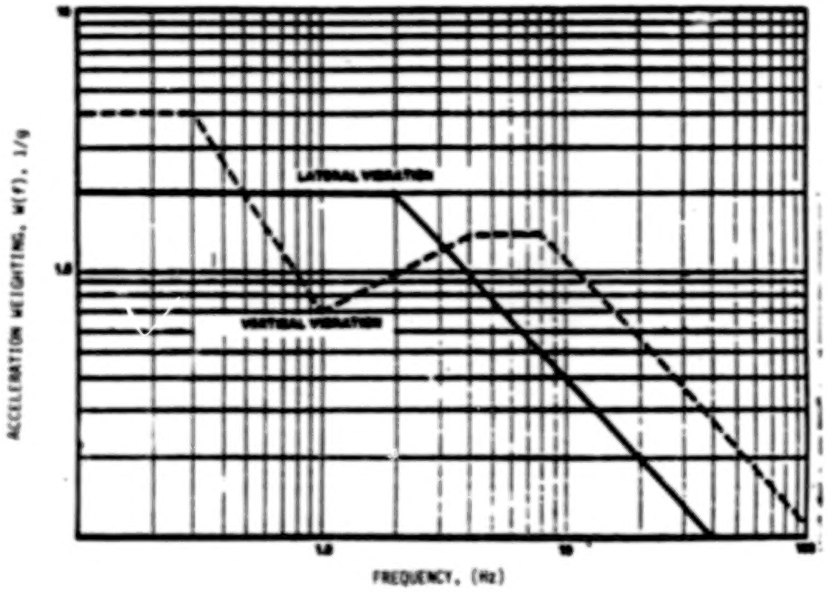
$T_{CS}(f)$ = TRANSMISSIBILITY AT CREW STATION, g/ft/sec

$\phi_g(f)$ = VON KARMAN GUST POWER SPECTRAL DENSITY OF INTENSITY (VERTICAL OR LATERAL GUST) SPECIFIED IN MIL-F-8785

f = FREQUENCY, Hz

f_t = TRUNCATION FREQUENCY (FREQUENCY BEYOND WHICH AEROELASTIC RESPONSES ARE NO LONGER SIGNIFICANT IN TURBULENCE)

RIDE QUALITY ACCELERATION WEIGHTING FUNCTIONS



For those of you who are not familiar with C*, the idea is just to get into the envelope shown. However, we have more than one design goal in the pitch axis of an aircraft. The other one is the MIL-F-9490 ride quality index. You can talk about gust load alleviation, which is certainly a pitch axis problem, and some other form of load control in the pitch axis. So we may have multiple goals for our future aircraft flight control designs. Multiple goals are best implemented with multiple surfaces. Admittedly you can attempt to implement all these goals with one surface, and in some cases you can do that. Gust load alleviation and ride quality, for instance, can be implemented typically with one set of surfaces.

FEEDBACK IMPROVES PERFORMANCE

- C^* FEEDBACK GOAL

  $|C^* - C_0^*| < \epsilon$

- FEEDBACK REALITY

  $C^* - C_0^* = \frac{1}{1+L}(D_0 - C_0^*) - \frac{L}{1+L}\frac{(N + \Delta T C_0^*)}{T}$

- CONSEQUENCES

  c1 $|1+L| > \frac{|D_0 - C_0^*|}{\epsilon}$, WHERE $L = GKT$

  c2 $|1+L| > |\Delta L|$; WHERE ΔL = PLANT MODELING ERRORS

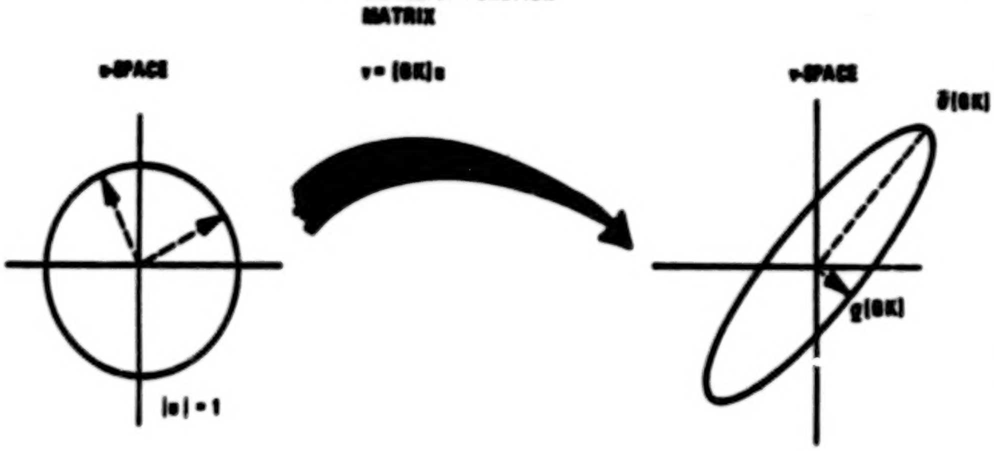
  c3 $\frac{|N|}{T} < \epsilon$ WHENEVER $L >> 1$

  c4 $\frac{|\Delta T|}{T} < \frac{\epsilon}{|C_0^*|}$ WHENEVER $L >> 1$

The idea for a single goal now is, in terms of the feedback performance issue, that we would like to have the actual commanded spec performed to a given command input to a certain error tolerance. In terms of feedback reality, L represents the combination of the control compensation and the plant of the vehicle itself with all its uncertainties. This simple equation really describes what is going on and you can see, quite simply, what happens. We would like to minimize this function to disturbance inputs, which may be big, and to command levels, which could be big also. And you can see quite simply that one way of doing this is to make L big, that is, high gain feedback. It certainly would support the goal. Another thing we want to avoid is transmitting all that noise into the system. Therefore we have certain constraints on L here.

Some meaningful consequences of all this is that $|1+L|$ is related to our spec in this fashion here, where your L is defined as the product of GKT. Now, one thing that I have not introduced is that L has certain errors. In the case of reconfigurable controls, one might postulate designing a single feedback control that would be robust to all failures. Such a notion is kind of ridiculous, I think. But we may want to look at certain types of failures that we could handle just by the basic feedback control. Actually, some people have studied this problem. The ΔL here normally represents just the normal uncertainty of the plant, which is considerable for a lot of airplanes. This could represent, in the normal sense, just the uncertainty with the structural model in which you have high frequency modes, the parameter uncertainties that you have after you have done your analysis and really do not know the vehicle, the actuator characteristics, etc. What I would like to throw in just for the sake of argument here is the possibility that the aircraft is changing, somehow, due to a failure. So, one can postulate, that one look at, say, a control system surface failure, using this model. I do not think that this is a very wise thing to do because G would change its dimensions. For instance, if you lose one whole row of G, you would have a significant change in the particular parameter by doing that. Other types of failures you might try to handle would be partial surface loss-maybe losses due to clipping the rudder off the control tower, or losses resulting from some sort of mid-air collision. Certainly, I have heard about some experiences with fighter aircraft in World War II where you actually lost part of the vehicle and yet you were able to maintain flight. In those cases they just got lucky, because there was no notion of feedback. So there are some things that you can look at just from the standpoint of feedback control that might enhance the robustness to certain types of failures.

"LARGENESS" AND "SMALLNESS" FOR MULTIVARIABLE SYSTEMS



- GK IS LARGE IF $\underline{\sigma}(GK)$ (SMALLEST AMPLIFICATION) IS LARGE
- GK IS SMALL IF $\bar{\sigma}(GK)$ (LARGEST AMPLIFICATION) IS SMALL
- $\underline{\sigma}, \bar{\sigma}$ ARE "SINGULAR VALUES" OF GK

I do not want to expand on the fundamentals of feedback control. I tend to agree with Mike. The situation is well at hand for those of us who have been using it for a while. I want to bring up the notion of singular values. For those of you who have never seen it before, it is basically a measure of the size of a matrix. And, in this case, you think of the old classical notions of gain and phase margins. The gain is the size of a single-input/single-output transfer function in complex space. If you are looking at the multi-input/multi-output role, you no longer have a single complex number. You are dealing with a matrix. So, how do you get from the classical notion of gain in the single-input/single-output role to the multi-input/multi-output role? The idea there is that you have got to look at a measure of how big that matrix is.

For instance, suppose the input to a GK, or some sort of a loop transfer relationship, is on the unit sphere. I am just showing a two-by-two system here that has unit magnitude. Then its output would be an ellipse. One useful way of measuring the size of the ellipse, short of actually going through and looking in every possible direction, is to measure its minor and major axes. And the singular values in this particular case are measures of the major axis represented by the maximum singular value and of the minor axis represented by the minimum. So what we try to do is relate control system design parameters to how they respond in terms of the maximum and minimum singular values.

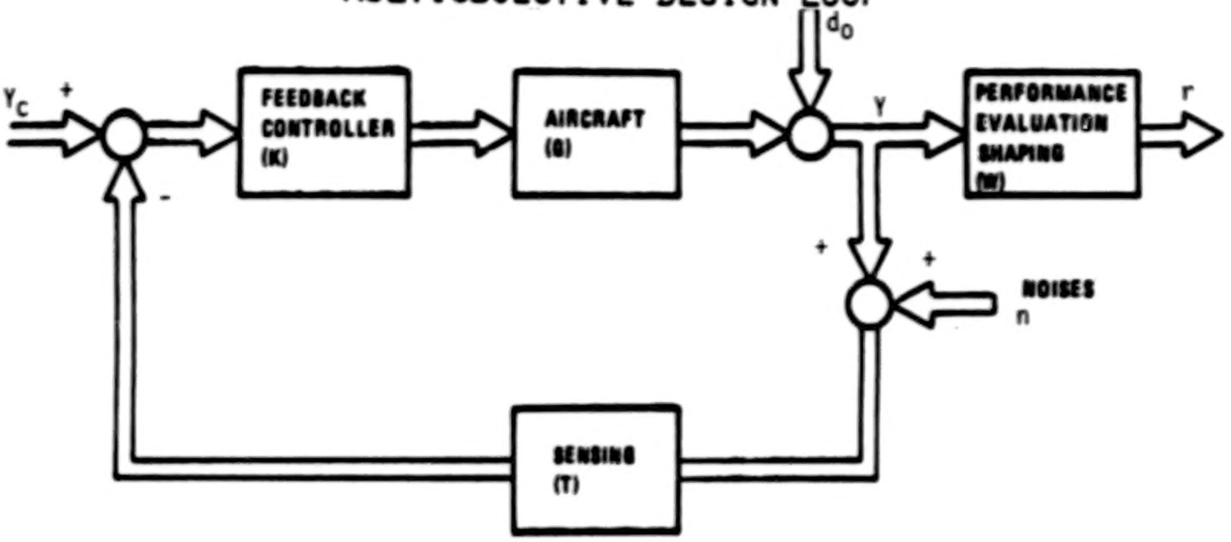
MIMO EXTENSIONS

CONSEQUENCES

- •1 $\underline{\sigma}(I+L) > \frac{\|D_0 - C^*\|}{\epsilon}$
- •2 $\underline{\sigma}(I+L) > \bar{\sigma}(\Delta L)$
- •3 $\|T^{1}N\| < \epsilon$
- •4 $\bar{\sigma}(T^{1}\Delta T) < \frac{\epsilon}{\|C_s{}^*\|}$

For instance, the same consequences we talked about before could be represented here. If we wanted to ensure that we could meet our performance goals, we would look at the minimum singular value of the loop transfer, in this case (I + L), to make sure that it was above our spec. In the case of robustness, we have to assure that the minimum singular value of (I + L) is greater than the maximum singular value of our perturbation. We will show some graphical interpretations of that. For instance, if L is very big, the minimum singular value has to be large also; likewise for noise properties.

MULTIOBJECTIVE DESIGN LOOP



$Y_c \overset{\Delta}{=} \begin{pmatrix} C_c^*, \text{ C* COMMAND} \\ n_{z_c}, \text{ NORMAL ACCELERATION COMMAND} = 0 \text{ FOR RIDE QUALITY} \end{pmatrix}$

$Y \overset{\Delta}{=} \begin{pmatrix} C^* \\ n_z \end{pmatrix}$

$d_o \overset{\Delta}{=} \begin{pmatrix} D_{oc}^*, \text{ DISTURBANCE, d, REFLECTED TO C* OUTPUT} \\ D_{on_z} \text{ DISTURBANCE, d, REFLECTED TO } n_z \text{ OUTPUT} \end{pmatrix}$

$r \overset{\Delta}{=} \begin{pmatrix} C^* \\ r_q, \text{ RIDE QUALITY RESPONSE} \end{pmatrix}$

THERE FOR

$W \overset{\Delta}{=} \begin{pmatrix} 1 & 0 \\ 0 & W(s) \end{pmatrix}$

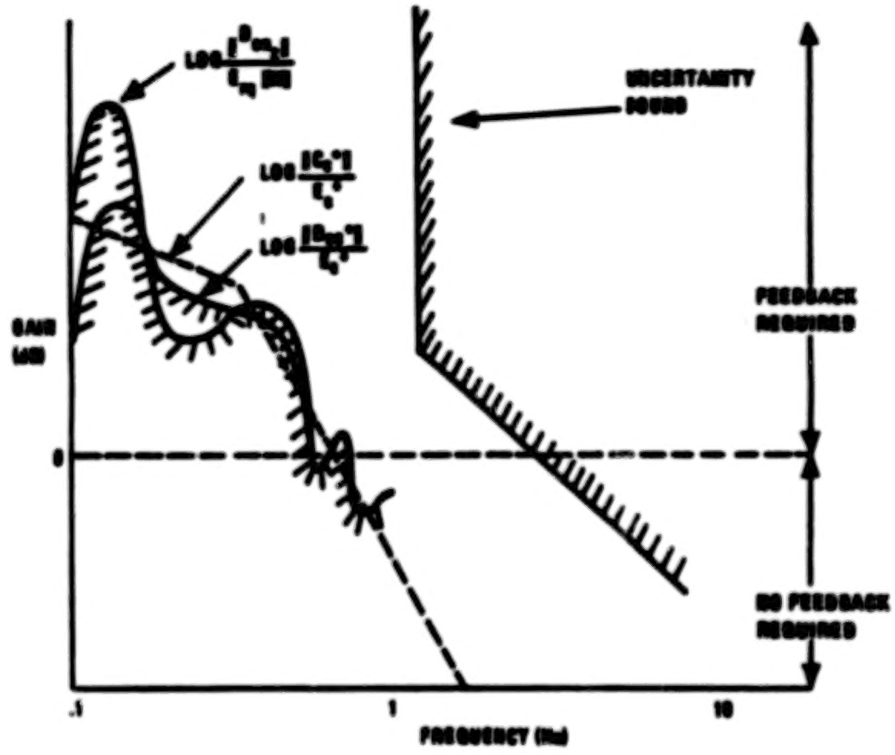
MULTIPLE DESIGN GOALS

CONSEQUENCES

- e1 $\underline{\sigma}(I+L) > \max_{\omega} \left\{ \frac{\|D_{oc}^*\|}{E_c^*}, \frac{\|C_c^*\|}{E_c^*}, \frac{\|W(S)\, D_{on_z}\|}{E_{r_q}} \right\}$
- e2 $\underline{\sigma}(I+L) > \bar{\sigma}(\Delta L)$
- e3 $\|T^{-1}n\| < \min_{\omega} \left(E_c^*, E_{r_q} / \|W(S)\| \right)$ WHENEVER $L \gg 1$
- e4 $\bar{\sigma}(T^{-1}\Delta T) < E_c^* / \|C_c^*\|$ WHENEVER $L \gg 1$

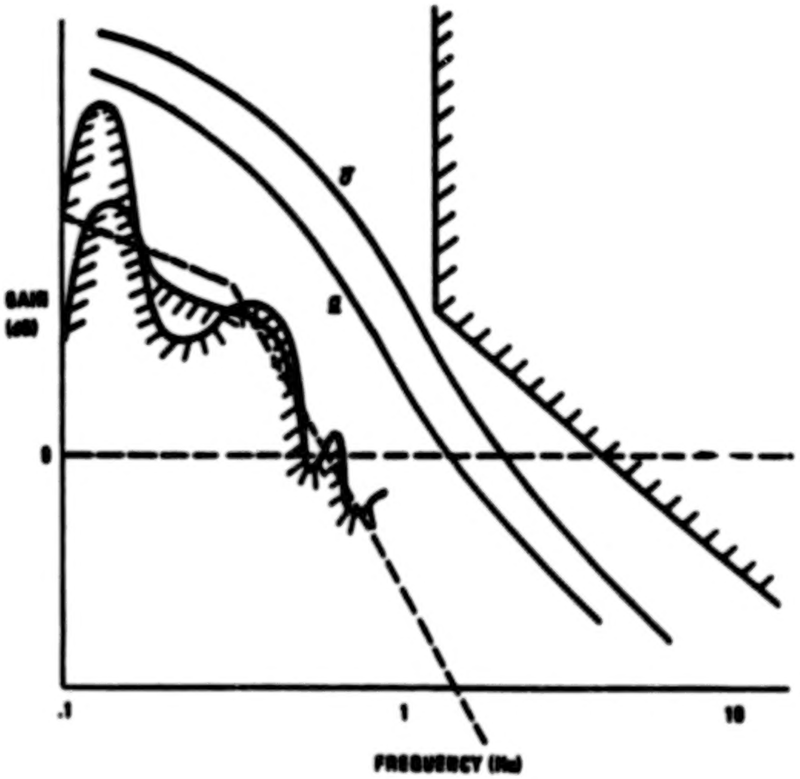
This might work in a system where we have two design goals. Now, let us say that we had two design goals here, the ride quality and C*. In the commercial world these might be just the normal handling qualities that we need of a relaxed static stability aircraft plus either ride quality or gust load alleviation, depending on what is advisable, at that point in time, in the pitch axis. Now we represent it as a matrix block diagram and we have the matrix elements K and G. So we generally have the same sort of situation as we did with singular control but now in the multi-input world.

GRAPHICAL INTERPRETATION



I would like to move on to some graphical interpretations of this. Performance goals, coupled with the uncertainty of the model, tend to give us certain regions where we would like the loop gain to fall. In the single-input/single-output role, we know that we would like high gain at low frequency, and we would like to roll off very nicely at high frequency. We would like good crossover properties. In this particular case, the commanded boundaries are representing C* and ride quality. The flight control handling quality issues typically tend to be at lower frequencies than gust load alleviation, so then I am just kind of generically representing that. We can meet our spec by ensuring that our minimum singular value is above this region here. Likewise, we have to be certain that we do not violate the bounds in frequency, in particular, of where we do not know the system.

MULTILOOP DESIGN OBJECTIVES



Now, what I would like to do is to relate this to our control system failure problem. If we lose an entire surface, the uncertainty goes across the entire frequency spectrum. Using the same control law quite likely will mean that we violate our uncertainty principle here. We no longer are dealing in a region where the maximum singular value can be achieved. If we do have some partial surface failures, particularly if we get into some flutter conditions, which is typically represented out here in high frequency, we may be able to recover from something like that with the current control law. Jurgen Ackerman of Germany has actually looked at the design of feedback control laws that have integrity to such failures. For instance, one of the primary goals of the control law is to be stable in the event that he loses a surface or a sensor. Some of the results are nice, but, unfortunately, I think he has compromised much of his primary system performance by imposing this integrity. For those of you who are not quite clear on this, the integrity in this sense means: what if I lost the use of a surface, but I did not detect it or isolate it, and I just wanted to be assured that the control system would be stable in the face of that. Now such things are possible, but I think that in the long run, we sacrifice too much system performance. So the idea of detecting, isolating, and reconfiguring certainly has more merit because "full up" primary performance is not compromised.

This is just one way of showing the impact of the current control law, assuming you are using feedback. Now, admittedly, current transports do not need feedback to remain stable. Future transports, I think, will have to. So, it is a way of saying that if you have got a good high performance control law in the primary loop, it is likely to have bad performance in the reversion modes. Of course, if you had low gains, if your command boundaries are really low and dictate low gains, you can probably survive a lot of changes at high frequency. However, the trends for highly augmented aircraft is certainly not for low gains.

LQG-BASED DESIGN METHODS

THE INVENTOR'S INTENT: TIME-DOMAIN OPTIMALITY

GIVEN

$\dot{x} = Ax + Bu + \Gamma\xi$

$y = Cx + \eta$

$r = Hx$

MINIMIZE

$$J = \lim_{T\to\infty} E\left\{\frac{1}{T}\int_0^T (r^T r + \rho\, u^T u)\, dt\right\}$$

A MEANINGFUL CONSEQUENCE: DIRECT SINGULAR VALUE LOOP-SHAPING

$$K(s) = K_c(sI - A + BK_c + K_f C)^{-1} K_f$$

$\sigma[GK(s)]$ DETERMINED DIRECTLY BY QUADRATIC WEIGHTS AND ASSUMED NOISE STATISTICS

SUGGESTED
LQG DESIGN PROCESS

STEP 1

FULL STATE LQ-REGULATOR DESIGN TO ACHIEVE GOOD LTFM SINGULAR VALUES

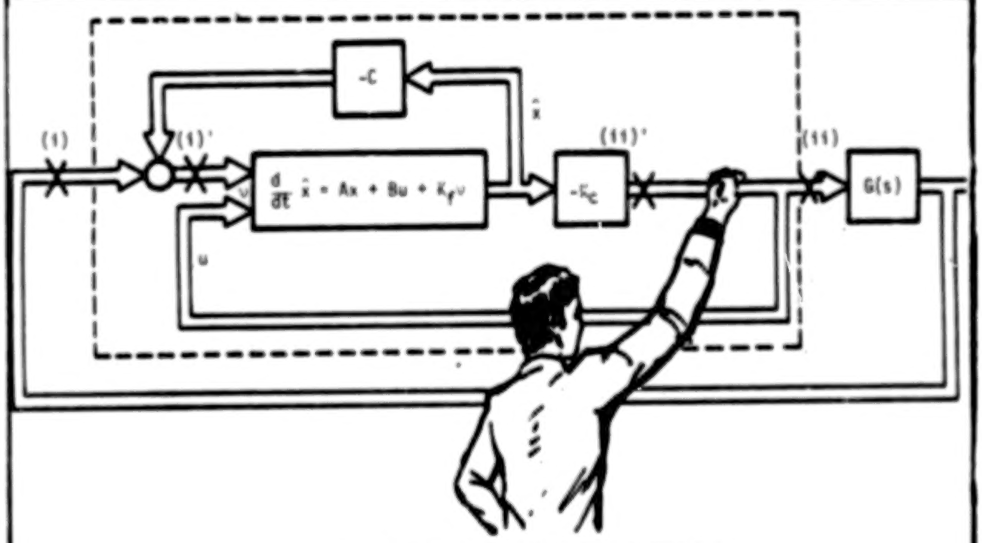
(OR DUAL)

STEP 2

LOOP TRANSFER "RECOVERY" WITH MODIFIED KB-FILTER DESIGN

(OR DUAL)

SIGNIFICANCE OF FULL STATE DESIGN



LOOP TRANSFER FUNCTION MATRIX (LTFM) PROPERTIES

LTFM AT (ii)' = $K_c\Phi(s)B$ (FULL STATE LQ REGULATOR)

LTFM AT (ii)' CAN BE RECOVERED AT (ii) WITH MODIFIED KB-FILTER DESIGN

DUAL

LTFM AT (i)' = $C\Phi(s)\Gamma$ (FULL STATE KB-FILTER)

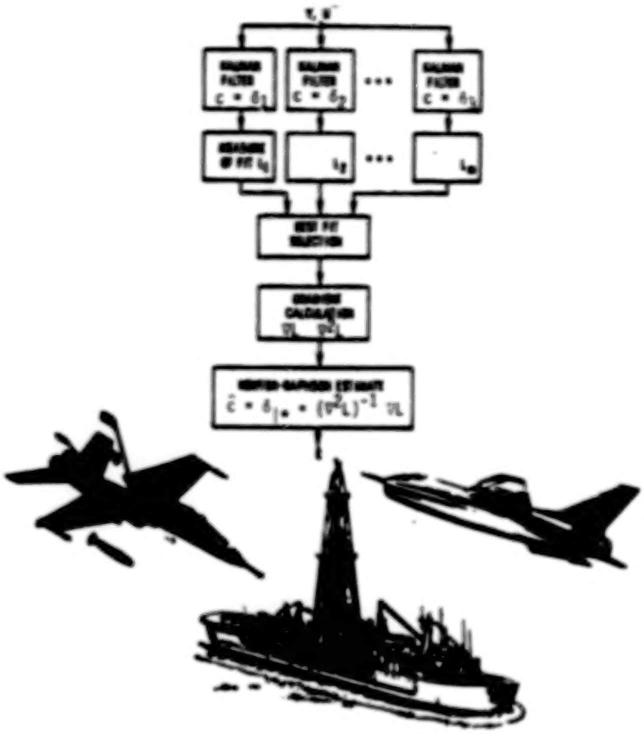
LTFM AT (i)' CAN BE RECOVERED AT (i) WITH MODIFIED LQ-REGULATOR DESIGN

The next set of viewgraphs basically talks about our approach to control law design. We have a technique using the LQG methodology. Gunter Stein, of our staff, has been looking at the problem quite a bit.

The inventor's intention here was basically time-domain optimization, where you can use the mathematics of linear, time invariant state space representations to minimize a certain performance index. This has always had some nice mathematical properties. Unfortunately, it is terrible from the standpoint of designing control laws because we have to deal with an uncertain world. It is great for modeling and it is great for computer synthesis of control laws because of the computer-nicey things like A's, B's, C's and H's.

However, the real world is handled better in the frequency domain. And what Gunter has shown is that you can get a frequency domain interpretation of this. For instance, this K compensator can merely be put in terms of the original A matrix, the B matrix, the C matrix which is the output coupler (these are the actual measurements that you have), and certain gains. This K_c is the full-state control law gain and this K_f is some sort of observer of gains that you have in the feedback loop.

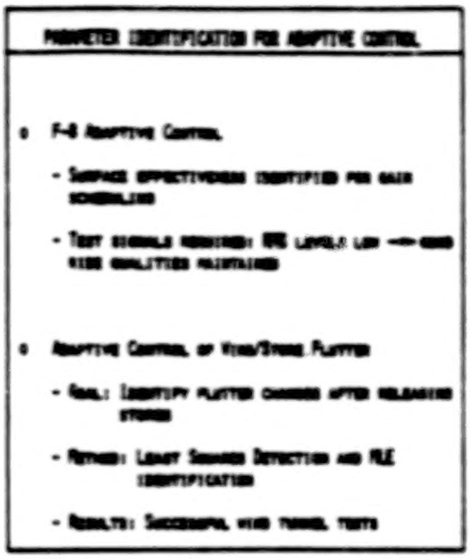
The idea here is that you want to design this compensator to have good frequency domain properties like the ones I alluded to on an earlier viewgraph. There are nice techniques for doing that, particularly for the singular values. You shape the particular K(s) to get good singular values of that. The issue we have been discussing here is whether that is even possible, in the face of such a massive change in the G matrix, to remain stable. The contention is that under certain failures this is true but under others it is not true.



- MAXIMUM LIKELIHOOD ESTIMATION
  - IDENTIFIABILITY ANALYSIS
  - PARALLEL CHANNEL IMPLEMENTATION
- MODEL REFERENCE ADAPTIVE CONTROL
- MODEL TRACKER ADAPTIVE CONTROL
- HIGH GAIN ADAPTIVE CONTROL
- APPLICATIONS
  - F-8 GAIN SCHEDULING
  - WING FLUTTER ONSET
  - DRILLING SHIP RISER ANGLE
  - HELICOPTER GAIN SCHEDULING

I would like to allude to one other particular thing that we have had some success with. This may create a little controversy after Mike Athans' statement about adaptive controls not working. Unfortunately, we have demonstrated adaptive control once or twice inflight and tested it in the wind tunnel. I think we have some really dreadful concerns about the way we are doing this. We ought to let the people at NASA Dryden and the people here at the wind tunnel know about it, i.e., maybe we should stop showing that it does work.

I think there is a good reason, however, beyond the controversy, for why this is working. Hopefully, we will do something current so Mike can criticize it. In any case, it works. A couple of experiences we have had with adaptive control bear some relationship to the problem we have talked about here.



PARAMETER IDENTIFICATION FOR ADAPTIVE CONTROL

- F-8 Adaptive Control
  - Surface effectiveness identified for gain scheduling
  - Test signals required: RMS levels low —> good ride qualities maintained
- Adaptive Control of Wing/Store Flutter
  - Goal: Identify flutter changes after releasing stores
  - Method: Least Squares Detection and MLE Identification
  - Results: Successful wind tunnel tests

The primary parameter identification portion of adaptive control is basically the technology we are developing. The control law implementation part of that was a highly bounded implementation. We used it for gain scheduling of the existing control laws with very significant bounds on how far those gains can travel, i.e., we did not let the system go unstable. The F-8 adaptive control law involves identifying surfaces effectiveness for gain scheduling. And the bottom line is that it works quite well. For the control laws in the F-8, the identification, particularly of the $M_{\delta e}$, the surface effectiveness of the elevator, was quite sufficient, and quite accurate enough to allow us to gain schedule throughout most of the flight envelope. I am not sure we tried the landing approach on the flight test data. I would have to check on that. We certainly ran through most of the flight conditions. In this particular case, surface effectiveness has a very nice linear relationship to $\bar{q}$. So you might say that we were identifying $\bar{q}$ in lieu of the air data system. As it turns out, that was the logical result. We could replace the air data system or we could do a reversion onto that air data system if it failed.

Real-time, on-line identification to try to detect changes in surface effectiveness of vehicles, however, requires test signals. These parameter identification schemes, by definition, go unstable if you do not provide some known excitations to the systems. That has been our experience. We did find, however, on the F-8 that the test signals required for that system were low enough that we did not upset the pilot's riding qualities. He did complain about it because there is an angle of attack nose boom out in front of the airplane and it started to wiggle.

Another adaptive control program that we have worked on with the Northrop Corporation that has had some success, and that I think might relate to our discussions, is what we call the adaptive control of wing/store flutter. The Air Force was and is interested in trying to maintain flutter mode control of an aircraft over an exhaustive number of stores that you might put onto the wing. You can imagine that an advanced fighter aircraft would want to exceed the speed regimes beyond the flutter boundary of the aircraft. In this particular case, we know flutter mode control works. We know we can provide feedback if we know what the plant is, if we know what the wings dynamics are. Our goal was to identify instantenous flutter changes after releasing the store without getting knowledge, say, from the weapons computer, that the aircraft had actually dropped the store. I, for one, and others have said "Well, why do you not just share the information with the weapons computer and forget about trying to change this thing adaptively?" Well, the problem is the Air Force would like to look at such an exhaustive number of stores that they want to see if you can do it adaptively. This was probably the single, most difficult adaptive control problem we ever tackled. And we recently had some success in the Langley wind tunnel at dropping a couple of stores off of a wing model. The methods we used were least squares detection and maximum likelihood identification. I will point out now that the control law we used in combination with this was again a simple, highly limited type of control law that did not allow us to get into more difficulties.

So there are two messages here for our group. One is that we can look at parameter identification for surface effectiveness, or perhaps for some other changes that could occur in the aircraft. It appears to us, from our fighter experience, that the RMS levels that we need for test signals would be low enough to attempt this. The wing/store results really surprised us. We did not think that we could do it. As a matter of fact, I am still skeptical that we can make instantaneous parameter identification. In one particular case we tried, when we dropped the store, the wing went from a stable flutter condition to an unstable one. We had to detect, isolate, and reconfigure in less than two seconds, and we were able to do that. This is a very high-risk technique though, but there is enough success here, I think, to warrant future looks at this type of technique for a more global role of control reconfiguration.

A CONCEPT FOR FCS RECONFIGURATION*

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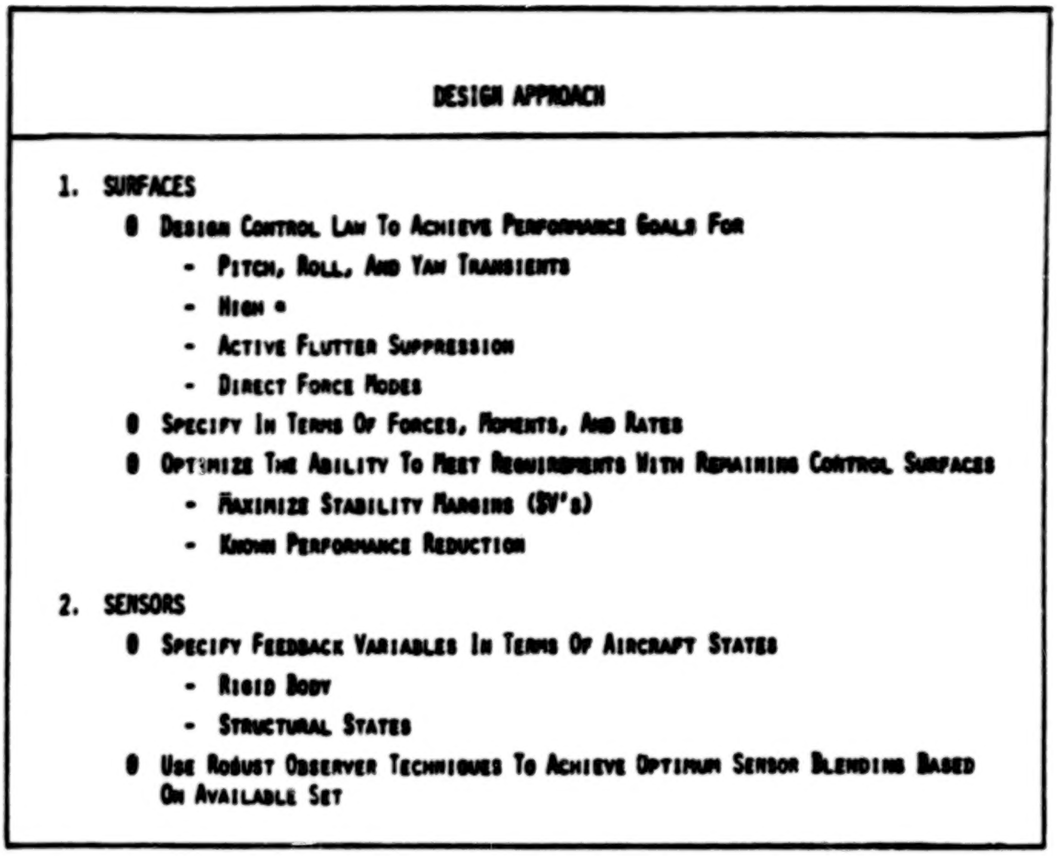
* PROPOSAL SUBMITTED TO DARPA

So, I would like to suggest, in finishing, that it is a critical thing to put all this together into a concept of flight control system reconfiguration. Here again I am alluding to the military. This next viewgraph shows a proposal that we have submitted to DARPA recently. I am just going to allude to one diagram that we have in this.



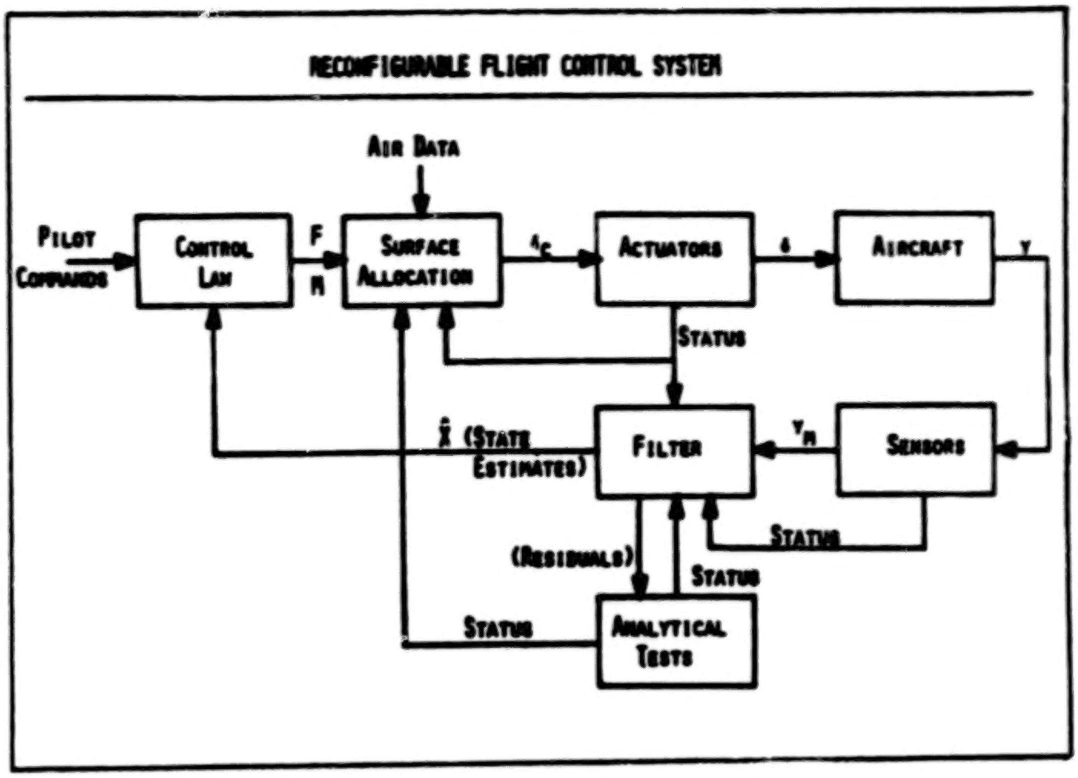
DESIGN APPROACH

1. SURFACES
   - ● Design Control Law To Achieve Performance Goals For
     - Pitch, Roll, And Yaw Transients
     - High α
     - Active Flutter Suppression
     - Direct Force Modes
   - ● Specify In Terms Of Forces, Moments, And Rates
   - ● Optimize The Ability To Meet Requirements With Remaining Control Surfaces
     - Maximize Stability Margins (SV's)
     - Known Performance Reduction
2. SENSORS
   - ● Specify Feedback Variables In Terms Of Aircraft States
     - Rigid Body
     - Structural States
   - ● Use Robust Observer Techniques To Achieve Optimum Sensor Blending Based On Available Set

In this particular case, we are showing our design approach for surfaces where we design primary control laws. One thing we would like to look at is specifying these control commands in terms of forces, moments, and rates, instead of actual surface positions. This is desirable because at any moment in time we may not know what surfaces are available to implement those control laws.

Now, for a given set of surfaces, we can have some notion of detecting and isolating failures. We would like to optimize those remaining surfaces to maximize a stated design goal, to maximize the stability margins.

I will not go into the sensors. That is, basically, some lower risk technology that a lot of people, like Honeywell and Draper, have already worked on.


RECONFIGURABLE FLIGHT CONTROL SYSTEM
AIR DATA
PILOT COMMANDS
CONTROL LAW
F
M
SURFACE ALLOCATION
δ_c
ACTUATORS
δ
AIRCRAFT
Y
STATUS
$\hat{X}$ (STATE ESTIMATES)
FILTER
Y_m
SENSORS
STATUS
(RESIDUALS)
STATUS
STATUS
ANALYTICAL TESTS

This, therefore, is a conceptual block diagram to implement such a control law. If we can construct a control law that commands forces and moments for primary performance, go into a block where we insert air data, the status of the sensors, etc., and go into a surface allocation algorithm based on knowing which surfaces are available, one has the structure to look at implementing the best possible set of performances that you have for the aircraft. In summary, I am suggesting a structure for one to look at before actually designing a control system.

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RESTRUCTURABLE CONTROLS
PROBLEM DEFINITION AND FUTURE RESEARCH

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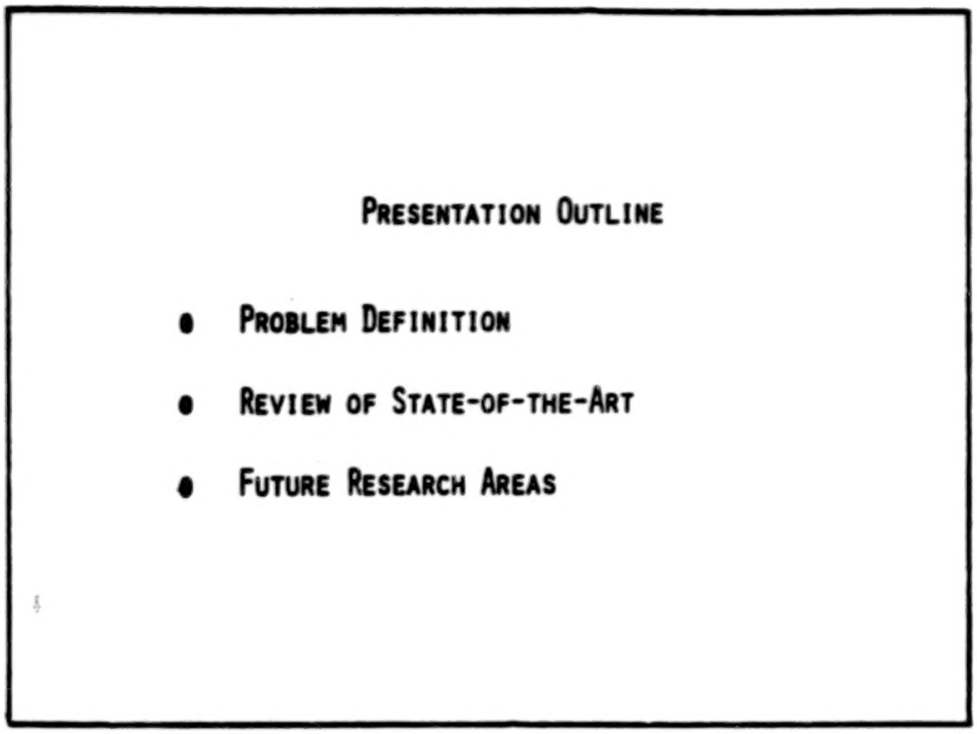


PRESENTATION OUTLINE

- PROBLEM DEFINITION
- REVIEW OF STATE-OF-THE-ART
- FUTURE RESEARCH AREAS

The approach that I took in putting the presentation together was more along the lines of trying to define the problem and then trying to identify some of the options that we have for future research.

RESTRUCTURABLE CONTROLS

OBJECTIVES FOLLOWING A SYSTEM FAILURE

1. STABILIZATION FOR THE CURRENT TASK
2. PROVIDE OPTIMAL HANDLING QUALITIES FOR ALL MISSION TASKS
3. ASSIST PILOT IN SELECTION FUTURE TASKS

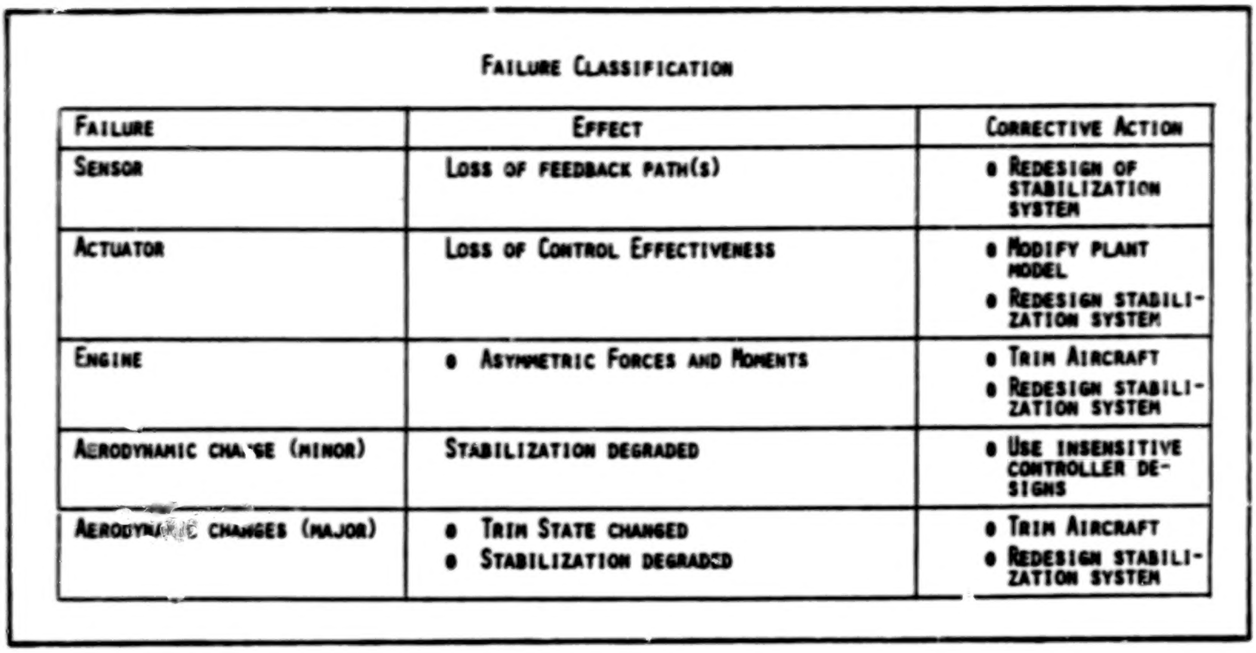
One of the points which was just brought up, which I think is crucial in trying to define the problem, is what, in fact, do you want the reconfigurable control to do? There are really three levels that can be discussed.

One is that immediately after the failure occurs you at least want to establish stabilization at that point. You want to provide that, but basically that really is not enough. There are other mission tasks that you want to accomplish. For example, if you are in climb out, you are going to want to establish a stabilized climb out; then you are also going to want to go through a cruise condition and finally get back down and land. And these three conditions require very different things from your controller. They are different problems.

Tom Cunningham pointed out that the handling qualities for these three missions are different enough that there are actually different MIL specs that cover designs for these conditions. So, this means that you not only have to do the reconfiguration once, but you have to do it two or three times.. Also you may not want just to land but to actually go all the way to the end of the original objective.

One of the interesting capabilities that you may want the system on board to have is to be smart enough so that, if you have had a failure and you automatically stabilize, the pilot can essentially query the computer and ask "can I change my airspeed by reducing it by 50 knots?" or "Can I change into this particular configuration?" The computer should be able to evaluate the reconfiguration potential at that new condition and be able to warn him that it would be a dangerous condition.

Again, with the DC-10, I think one of the problems the pilot had was that he slowed down for some reason or another. If he had maintained his speed, he would not have had a problem. So a lot of times, even though you stabilize the situation, and perhaps identify what the mission is or what the failure was, the pilot still may not know what his available options are. So either you have the computer present him with the things that he should do, or let him query the computer as to the different options he can think of and have the computer provide him with the consequences.



FAILURE CLASSIFICATION

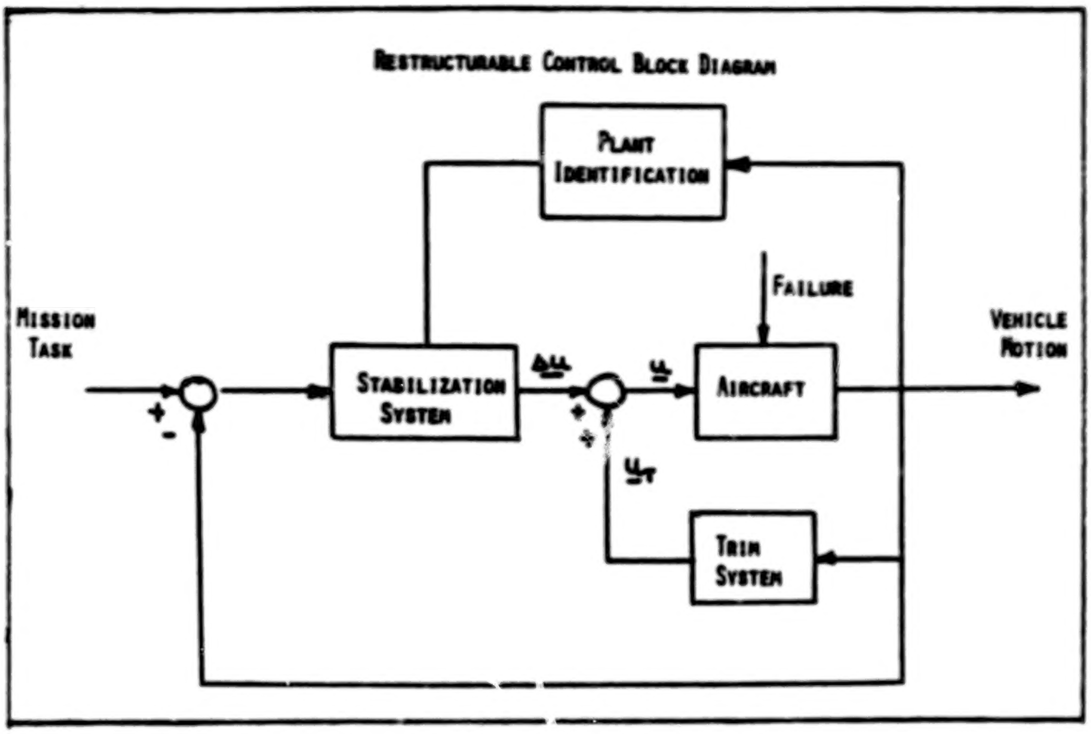
FAILURE	EFFECT	CORRECTIVE ACTION
SENSOR	LOSS OF FEEDBACK PATH(S)	• REDESIGN OF STABILIZATION SYSTEM
ACTUATOR	LOSS OF CONTROL EFFECTIVENESS	• MODIFY PLANT MODEL • REDESIGN STABILIZATION SYSTEM
ENGINE	• ASYMMETRIC FORCES AND MOMENTS	• TRIM AIRCRAFT • REDESIGN STABILIZATION SYSTEM
AERODYNAMIC CHANGE (MINOR)	STABILIZATION DEGRADED	• USE INSENSITIVE CONTROLLER DESIGNS
AERODYNAMIC CHANGES (MAJOR)	• TRIM STATE CHANGED • STABILIZATION DEGRADED	• TRIM AIRCRAFT • REDESIGN STABILIZATION SYSTEM

This viewgraph lists various failures, the effects of these with regard to the controls, and the corrective action required. For completeness, I also included the sensor failures even though that was not a part of the control ground rules. I have violated several of the ground rules in the assumptions provided so as to present a little bigger overview.

The loss of sensors is like losing feedback paths and in doing that you have to be able to design a controller with a restricted number of feedback paths. There is some theory available for designing limited state feedback controllers. It is unclear if this can be done in real time.

The loss of control effectiveness or control power, if you lose an actuator, requires the redesign of the stabilization system.

A different kind of problem occurs with engine failures or aerodynamic changes. This is the introduction of trim changes. As everybody has mentioned it, this is crucially important because quite often when you think about control design, you are dealing primarily with the perturbation controllers. Trim is an altogether different problem. And probably for many cases if you could reestablish a trim, the majority of the problem would be solved.

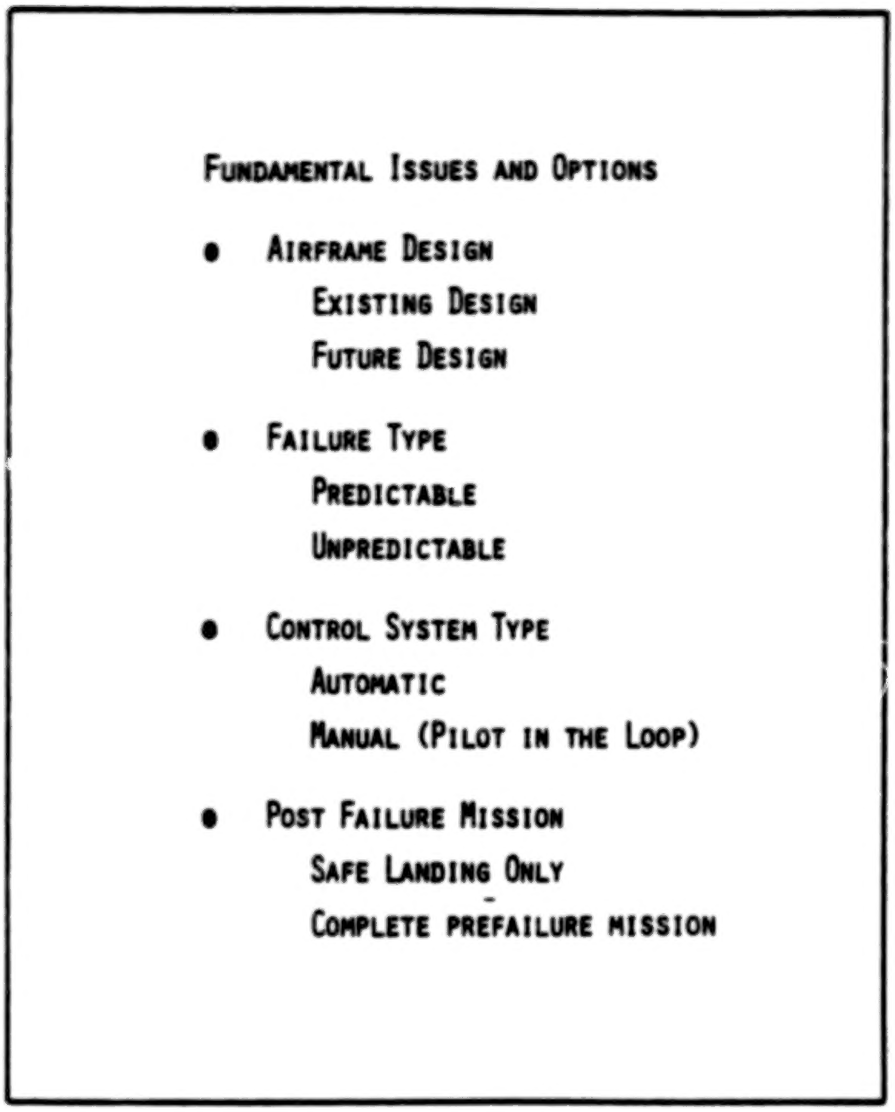

RESTRUCTURABLE CONTROL BLOCK DIAGRAM

PLANT IDENTIFICATION
FAILURE
MISSION TASK
VEHICLE MOTION
+
-
STABILIZATION SYSTEM
Δu
+
+
u
AIRCRAFT
u_T
TRIM SYSTEM

This viewgraph presents a block diagram to show, conceptually, the three pieces that we are talking about. Notice that you have got a stabilization system, a trim system, and some kind of plant identification.

Given the fact that we know what the mission task is, and if you are required to reconfigure, you have to let the computer know the mission. Also, after the failure has occurred some kind of identification of the plant is required. I purposely used plant rather than parameter because, here again, we are not talking about just the perturbation models and the stability derivatives. Finally, I have explicitly shown a trim system.

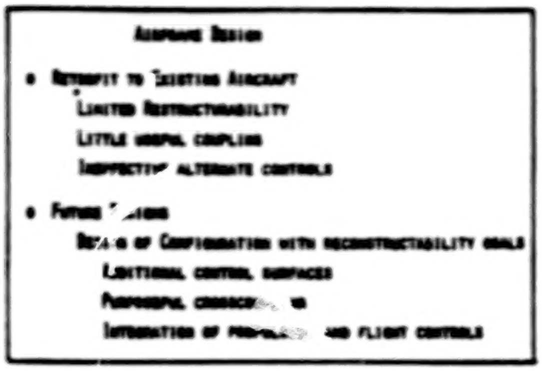
Although the three pieces are shown separately they could be mechanized in one computer.



FUNDAMENTAL ISSUES AND OPTIONS

- AIRFRAME DESIGN
  - EXISTING DESIGN
  - FUTURE DESIGN
- FAILURE TYPE
  - PREDICTABLE
  - UNPREDICTABLE
- CONTROL SYSTEM TYPE
  - AUTOMATIC
  - MANUAL (PILOT IN THE LOOP)
- POST FAILURE MISSION
  - SAFE LANDING ONLY
  - COMPLETE PREFAILURE MISSION

To design such a system there are several fundamental issues that have to be decided. These include the airframe design, the failure type, the control system type, and the post-failure mission.



Airplane Design

- Retrofit to Existing Aircraft
  - Limited Restructurability
  - Little useful coupling
  - Ineffective alternate controls
- Future Designs
  - Design of Configuration with reconstructability goals
    - Additional control surfaces
    - Purposeful crosscoupling
    - Integration of propulsion and flight controls

Now I want just to talk briefly about each one of these starting with the aircraft design. There are two categories within this issue.

One is the retrofit of existing aircraft. There is really a limit to what we can do as control designers because, first of all, there is little useful coupling between the various variables. In fact, if you want to design an aircraft, you would like to get rid of all the cross-coupling effects. If we have done a fairly good job of that aerodynamically, and now we want to go back and use coupling for reconfiguration, we do not really have a very good opportunity. Also the alternate uses of control surfaces in existing configurations are not very effective. One of the examples that I am aware of using alternate controls is that to make perturbations in the roll angle, you can apply rudder which creates a sideslip, which then creates a roll rate. Thus you can use rudder to adjust the roll angle if you are dealing with small angles. So, although we actually have some coupling for current aircraft, it is really not very effective and could not be used to make large changes.

For future designs, we have a chance to do something very different. One of the things that we, as control engineers, should almost demand is the opportunity to be involved in the configuration design. Usually a control designer is given an aircraft and told, make this vehicle work. We cannot really afford to do this anymore. The design of the airframe and the control system is an integrated function. It is really something that is required and offers a lot of opportunity. For example, we have talked about the addition of control surfaces. Also you could build in purposeful cross-coupling, so that you could turn a rudder into a more effective roll-rate device. The coupling during nonfailed flight could be handled by the vehicle's SAS. Therefore, one could take out all the unwanted coupling in a nonfailed condition and yet provide the coupling capability when you did have a failure. Another example is using the propulsion system as another control device.

FAILURE TYPE

- Predictable Failures
  - Multiple Precomputed Designs
  - Failure Identification
  - Controller Design Selection and Implementation
- Unpredictable Failures
  - Failure Identification
  - System Identification
  - Controller Redesign and Implementation

In terms of the failure types, you have to consider both predictable and unpredictable failures.

Regarding predictable failures, there is an awful lot that we can do. For example, multiple, precomputed designs provide a way of handling these failures. It would seem that you could actually handle a great deal of the existing problems just by worrying about predictable failures. If unpredictable failures imply that no a priori analysis or design can be done, then you have a much more difficult situation.

For the unpredictable cases, you basically have to go through the failure detection, the system for plant identification, and then actually perform an inflight redesign. All these things have to be done in the blink of an eye. And, right now, I have my doubts whether that is something that we will see very shortly.

CONTROL SYSTEM TYPE

- AUTOMATIC
- MANUAL
  - GOOD HANDLING QUALITIES REQUIRED FOR ALL MISSION TASKS
  - PILOT - CONTROLLER COMMUNICATION ESSENTIAL
  - MISSION TASK SELECTED BY PILOT

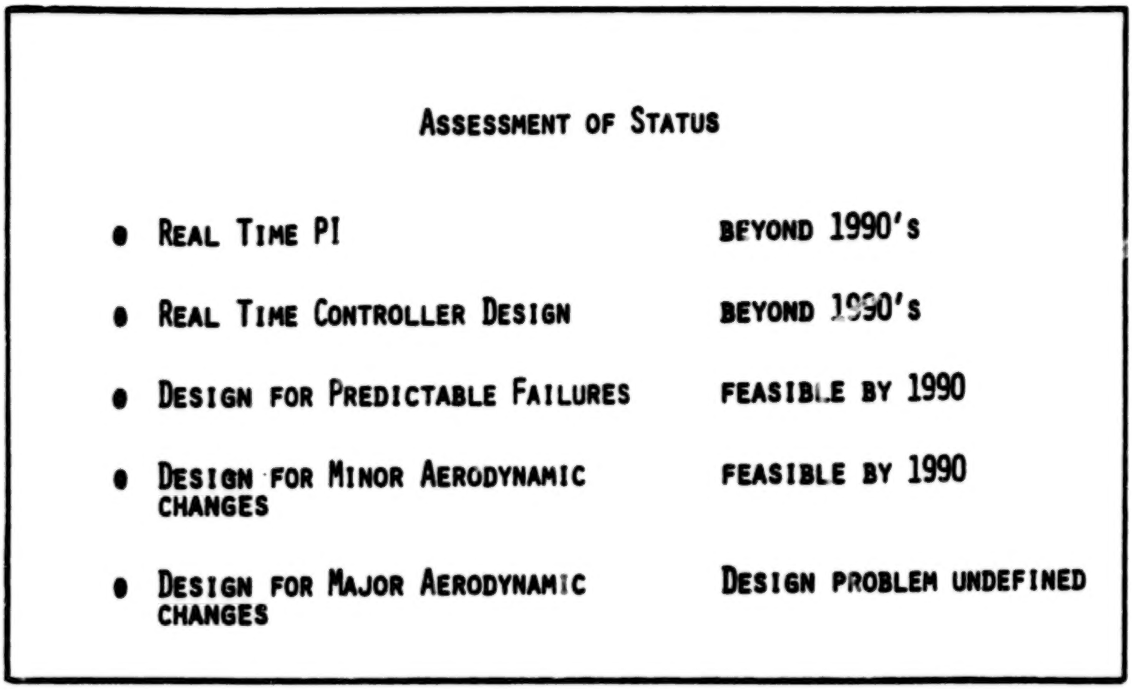
Another of the fundamental issues is whether this is going to be an automatic or a manual system.

I think the only way the automatic mode is going to be acceptable, especially for commercial airlines, is at the instant of failure. When a failure occurs, you are going to want the system to automatically take over and stabilize the aircraft. This is, however, all you are going to want the system to do. You are going to want it to reconfigure itself, but only at the request or with the interaction of the pilot. Pilots are not going to let you go beyond that. You know, this idea of you getting up in the air and having a failure, and the computer says, "okay, you can go get a cup of coffee now, I will take it down and land it," is not something that is very feasible. It may be something that is technically possible to do, but it is something that just would not be acceptable to the pilot. Therefore, if there is going to be a manual system and the pilot is going to have to fly this reconfigured vehicle, you have got to be very careful about providing the best handling qualities within the remaining capability. This requires careful consideration of the interaction between the pilot and the system.

POST FAILURE MISSION

- SAFE LANDING
- COMPLETE "ORIGINAL" MISSION
- GET THE PILOT OUT (MILITARY)

We also talked about the post-failure mission as being one of two extremes. One extreme is that I just find a field somewhere, hopefully it has a runway on it, and all I really want to do is land safely. The other extreme is the requirement to complete the original mission or some alternate mission. The post-failure mission will depend strongly on the application. A commercial airliner would most likely require only a safe landing whereas a military mission might put a high priority on continuation with the original mission.



ASSESSMENT OF STATUS

• REAL TIME PI	BEYOND 1990'S
• REAL TIME CONTROLLER DESIGN	BEYOND 1990'S
• DESIGN FOR PREDICTABLE FAILURES	FEASIBLE BY 1990
• DESIGN FOR MINOR AERODYNAMIC CHANGES	FEASIBLE BY 1990
• DESIGN FOR MAJOR AERODYNAMIC CHANGES	DESIGN PROBLEM UNDEFINED

I tried to make a rough guess as to where we are in certain technology areas. I broke it down into two time intervals, the 1990's or beyond. This is not terribly different than what Mike Athans said earlier. His, of course, was a lot more detailed. But, one of the things that we can agree on is that unpredictable failures which require real-time parameter identification or plant identification and real-time controller design are still very far in the future. If you drop back to predictable failures or minor aerodynamic changes, solutions should be very feasible in the next eight years. Although we can solve this class of problems, research is required to demonstrate the feasibility of such a system.

A problem which requires extensive research is reconfiguration following major aerodynamic changes. This class of failures involves major trim changes and important nonlinear effects. Little has been done to assess the size of reasonable failures of this type. One way to help define this problem is to investigate the battle damage for military operations. As Tom mentioned there are all kinds of pictures of B29's and B17's with their tails virtually shot off that somehow limped back. Therefore, the first order of business is to collect data to bound the problem. Then we could have a better idea of how long it is going to take to solve it.

TOPICS FOR FUTURE RESEARCH

- MEASURE OF AIRCRAFT CONFIGURATION RESTRUCTURABLE POTENTIAL
- AIRFRAME CONFIGURATION AND FLIGHT CONTROL SYSTEMS INTEGRATION DESIGN PROCEDURES
- PLANT IDENTIFICATION TECHNIQUES
- CONTROLLER DESIGN TECHNIQUES
- RESTRUCTURABLE CONTROL CONCEPT VERIFICATION TOOLS

Now, in terms of the new research areas that I see, I would first like to tell you about the concept of "noble goals." It turns out that model reference adaptive control at one time was one of my "noble goals." It is just an absolutely super idea, if they could ever make it work. I also had been through the problem of trying to make it work in very simple cases, and gave up on that about four or five years ago.

One of the things that would be another "noble goal" is if we could actually have some measure of the reconfigurability for a particular configuration. Maybe this is some kind of a wild dream again, but it is in fact something that we should attack. There are really two reasons for that. One is that if we are given a configuration, it would be nice to be able to determine its potential for reconfiguring before we actually get off and start designing controllers for it.

The second thing, in terms of the utility of such a metric, is as a spec for the design of the airplane. In other words, you not only have a performance spec, you have a mission spec, and you also have a reconfigurability spec. That would be kind of interesting since that would allow the control designer to get into the loop earlier in terms of configuration design. This really gets back to the idea that the airframe, reconfiguration, and the flight controls design really have to be done together. We cannot afford to do things separately or try to patch up what the aerodynamicists have done to us inadvertently.

There are three other areas that we have yet to address: plant identification techniques, controller design, and the restructurable control concept verification tools.

PLANT IDENTIFICATION

- EFFICIENT METHODS OF IDENTIFYING "FULL" MODEL
- SIMPLIFIED METHODS FOR REAL TIME IDENTIFICATION

In the area plant identification I would like to discuss two areas. The first is real-time parameter identification using simplified methods that can be implemented in an onboard computer. One way to think about parameter identification is just as a very sophisticated curve-fitting technique. The programs used have been refined to give estimates of the parameters for reasonable data inputs. However, there is a lot of extra degrees of freedom that allow us to get multiple solutions from the same data. So the problem then is not to get a solution, but to get the right solution, i.e., the accurate model of the aircraft. I fear that inflight real-time parameter identification might be another of the "noble goals."

The other main area involves only the predictable failures. For this case we will want to do parameter identification for all the different configurations. This may be done either theoretically, experimentally, or by a combination of the two. For this we have the curse of dimensionality compounded by the fact that in addition to the standard stability derivatives and the control effectiveness, you are also going to want to identify coupling terms that are usually ignored. Also, you are going to want to identify coupling through the control power terms which we normally ignore. For example, we normally do not think about the pitching moment due to the rudder, but now that may in fact be an important factor. Finally, we want to develop models of the airplane with failed components, e.g., asymmetric trim conditions. Therefore, one is presented with a multitude of different flight conditions, and configurations, that require models. If flight tests are required, this would be extremely expensive. Research is therefore required to develop efficient model determination techniques.

CONTROLLER DESIGN TECHNIQUES

- EMERGENCY AUTOTRIM SYSTEM DESIGNS
- SIMPLIFIED "OPTIMAL" CONTROL DESIGN PROCEDURES
- EFFICIENT LIMITED STATE FEEDBACK
- DESIGN PROCEDURES FOR NONLINEAR SYSTEMS

There are several categories of control design procedures that are applicable to the restructurable situation. One of the major ideas is an emergency autotrim system that is at the heart of the problem. If you can retrim the aircraft after a failure, the pilot could fly the aircraft and diagnose his situation. This implies a very high authority, fast responding system which may not be acceptable to the pilots. This would be different from standard trim systems which are very slow responding and of limited authority. To design an autotrim system we must assure that we have no false alarms. All you need is one false alarm and the system would never get turned on again.

We have talked about optimal control design procedures and simplifying those so they can be done on line. One that would be applicable is limited state feedback. This technique is now used to design control systems where you want to limit the number of either sensors or states. For example, you want to actually reconfigure or redesign in a limited state sense where you basically now eliminate the feedback loop associated with the failed sensor. This procedure requires a reasonable amount of time on a mainframe computer at present so that more efficient design algorithms are required.

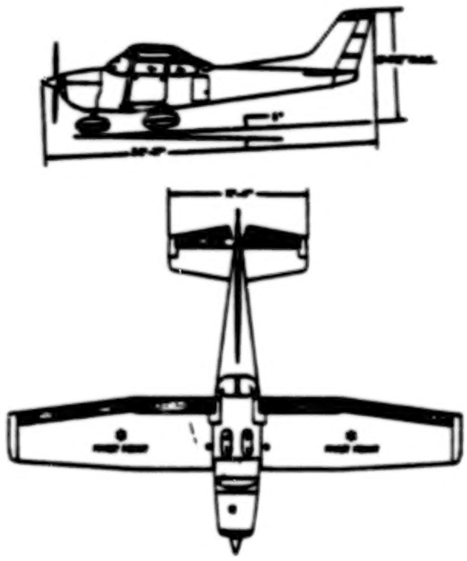
The last of the design techniques is an attempt to attack the nonlinear problem directly. Directly attacking the nonlinear problem is another of the "noble goals." This does not seem feasible in the near future.

RESTRUCTURABLE CONTROL CONCEPT VALIDATION TOOLS

- THEORETICAL PREDICTIONS
- BATCH SIMULATION
- REAL TIME SIMULATION
- FLIGHT TEST
  - MODEL TESTS
  - FULL SCALE

If we are successful at developing restructurable techniques, the next main issue is their verification. How well we do this will have a big impact on their ultimate acceptance. To do this, we have theoretical predictions, batch and real-time simulations, and ultimately flight verification. I believe that the flight verification of these techniques is essential. I also believe that proof of concept demonstration can be done using research aircraft.

ADVANCED CONTROL CONCEPT TEST VEHICLE



- MULTIPLE INDEPENDENT COMPUTER CONTROLLED CONTROL SURFACES
- DEDICATE CABLE DRIVEN CONTROL FOR SAFETY PILOT
- INSTRUMENTATION PACKAGE
- GENERAL PURPOSE COMPUTATION SYSTEM

One of the concepts that we have at the University of Kansas which would allow us to do that in a efficient way is pictured on the viewgraph. The concept is to take the existing control surfaces and split them. You would essentially then have many surfaces, each of which is independently drivable or controllable by the computer. One set of surfaces would be connected to the cable system to retain an independent safety pilot system for the airplane. The remaining surfaces could be used in two ways.

One way is that you can simulate failures by using some of the control surfaces as the failure mode generator to generate asymmetric loads or just loads in the failed actuator. The remaining surfaces could then be used for reconfiguration. This aircraft would allow the verification of the general concepts worked.

Another idea that would be very desirable would be to pick the size so that all the surfaces can be driven by the same type and size actuator. One of the problems that exists when there are multiple surfaces on an airplane is the fact that each surface requires its own kind of actuator. This would cause a problem with the military because of the cost of maintaining equipment with a large number of dissimilar components. I do not think that it is necessary to use different servos. You can be clever in the way you size the controllers and position them so that you can use a common servo or a common actuator.

Conclusions and Recommendations

- Major Improvement in Safety through a new Controller Design Philosophy Feasible
- Two Phase Program Desirable
  - Near Term - Predictable Failures
  - Far Term - Unpredictable Failures
- Well-Defined Problem and Program Goals Essential
- Integration of Aircraft Configuration and Controller Design offers Maximum Impact
- "Real World" verification of Concepts Essential

In terms of closing, these are my conclusions and recommendations. It looks like we really do have a concept that can be attacked and has the potential to provide a major improvement in safety. This concept can be researched through a program formulated from this workshop or other related areas. We really should not ignore investigations for possible near-term solutions, e.g., solutions to predictable failures. I think there is a lot to be gained by collecting the available technology and actually showing that it works for predictable failures. At the same time, we should look at far-term concepts by investigating some of the basic theories that are really going to be needed for the concept of unpredictable failures and the more difficult problems, e.g., large aerodynamic changes. The real key to it all is the fact that whatever report comes out of the workshop should have a very well defined problem. The goal of the workshop is thus to try to identify the problem, what goals to set for a program of research, and how far to scope the research.

Finally, I would like to stress two points. First the integration of the configuration and the controller really offers the maximum impact. And second, I believe very strongly that you are going to have to do some real world verification of the concepts if you really want it to be accepted by the industry.

EXPERIMENTAL EXPERIENCE AT CALSPAN

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Introductory Remarks

I want to share with you my ideas on the subject of restructurable controls. As an introduction, I would like to relate the experience we had with one of our aircraft, a T33, which I think vividly illustrates the possibilities that exist today for restructuring the control system of an aircraft.

During a research flight in our T33, the aircraft developed a severe wing flutter problem. Fortunately the aircraft was protected with explosive bolts, so that within a few milliseconds the explosive bolts sensed the flutter and blew off both wingtip tanks. As a result, damage was incurred by the outer third of the starboard wing (which essentially disintegrated) including half of the aileron. Also, the port wing warped considerably. Nevertheless, the pilot was able to bring it in without flaps at approximately 200 knots. Therefore, this was a survivable type of a sudden, restructed aircraft. We had not only restructured controls because we had half of the starboard aileron, but we also had a restructured aircraft because we lost about a third of the wing. This type of experience has led us to consider this type of problem much more seriously than we had in the past. The Air Force has flown this aircraft very successfully for many thousands of flight hours since 1955 using a fly-by-wire with feedback, analog control system. The Air Force is presently in the process of replacing this aircraft with an aircraft in which they want considerably more control versatility, in terms of having control over all six degrees of freedom of motion and maybe more as well. The three leading candidate airplanes are the F-5, F-18, and F-16. Because we are talking about 3 or 4 years from now as far as cutting metal is concerned, we have an opportunity at this stage of the game to look at, consider, and to study the restructurable controls problem so that an aircraft can be available or can have the versatility required to do the type of research that we will be discussing this afternoon.

PARTIAL LIST OF CONTROLLERS

Name	Primary Function	Secondary Effects
Traditional		
- Elevator	pitching moment	Z force
- Aileron	rolling moment	—
- Rudder	yawing moment	Y force
More Recent		
- Servo throttle	X force (Z force)	pitching moment
- Direct lift flaps	Z force	pitching moment
- Collective ailerons	Z force	pitching moment
- Canard surfaces		
horizontal	pitching moment	Z force
	rolling moment	
	Z force	pitching moment
vertical	yawing moment	Y force
	Y force	yawing moment
- Spoilers	rolling moment Z force	
- Differential throttle	yawing moment	pitching moment
- Differential elevators	rolling moment	
- Speed brakes, split rudder	X force	
- Leading edge slats	Z force	
Most Recent		
- Thrust vectoring	pitch, yawing moments	X, Y, Z force
- Inlet	yawing moments	

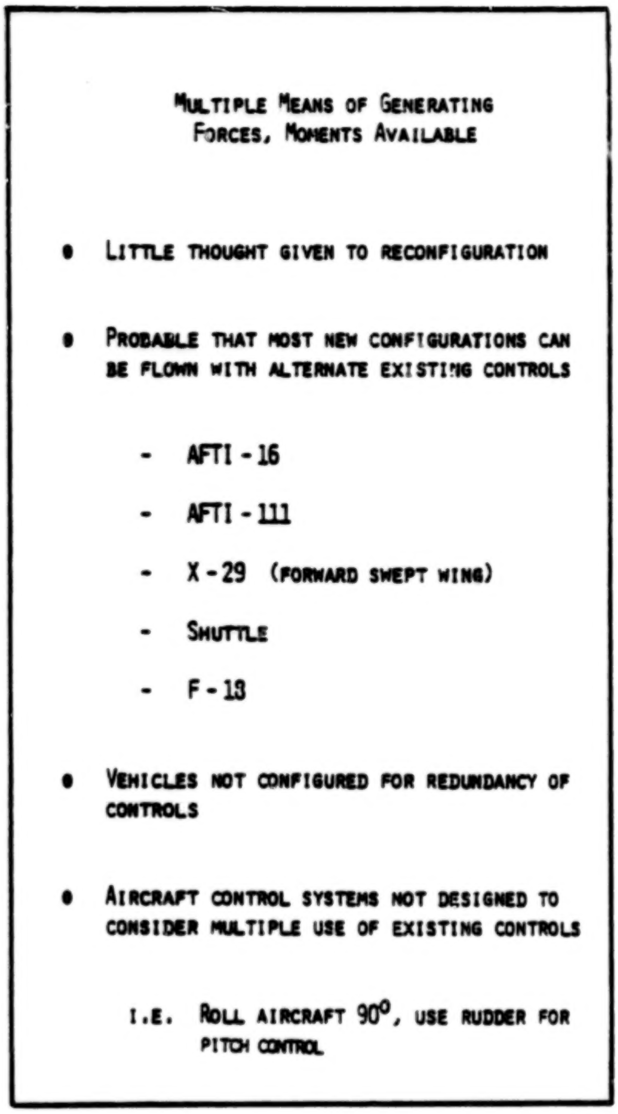
With that introduction, let us get on to a more mundane type of discussion which is almost academic. We start out with the traditional type of surfaces--the elevator, the aileron, and rudder--and list the primary function of each--which is pitching moment, rolling moment, and yawing moment, respectively. But each one of these controllers has secondary effects. The elevator, of course, produces a vertical force as well as a pitching moment because it is a lifting surface. The rudder produces not only yawing moment but a Y-force, or lateral force, as well.

Then we go on to more recent types of control devices that have been implemented in aircraft. The servo throttle produces an X-force or a Z-force, or both, and also a pitching moment, depending upon how the engines are located and mounted on the airplane. Nowadays the throttle, even manually, is used quite often. For instance in the carrier landing case, one thinks of the elevator and the stick as the primary controllers as far as pitching moment is concerned. Yet on a carrier landing, a pilot may use the elevator to control his angle of attack or velocity, and he may use his throttle to control his flight path angle. This, in a sense, is a switch in the conventional role of controllers and how the pilots use them. Therefore, even today, there is more than one primary task for several of the controllers that are available on aircraft. The direct lift flaps produce primarily a Z-force, or direct lift force, but can also produce a pitching moment, depending, of course, on their location with respect to the CG of the aircraft. Collectively operated ailerons are essentially the same thing as the direct lift flaps, but if you have swept-back wings and the ailerons are located farther outboard, then you could have more pitching moment than with the inboard direct lift flap. The more recent aircraft have cannard surfaces, which are horizontal or vertical, and produce pitching moment, rolling moment, and Z-force. The secondary effects could be Z-force but, depending on how they are mounted and how they are designed, any one of these can be the primary and the other the secondary function, or you do not even have to define which is primary and which is secondary. Vertical cannard surfaces can produce a yawing moment or a Y-force, and then the secondary function is either a Y-force or a yawing moment, depending entirely on where they are located on the aircraft. Therefore, the location of the surfaces on the aircraft is just as important as what kind of surfaces they are. This is also true for sensors. The sensors have two primary functions and there are at least two primary design considerations--what they sense and where they sense it on the aircraft, both of which are very important. And there is a direct analogy between this and the surfaces that can be put on aircraft as well.

Then there are spoilers which produce rolling moment and Z-force because they destroy lift. There are differential throttles for yawing moments and pitching moments, depending again on where the thrust acts with respect to the coordinates of the aircraft, and there are also differential elevators. Speed brakes and split rudder are for X-force control.

Most recent and probably one of the most useful devices is thrust vectoring, or an equivalent. This is because probably the most difficult thing to compensate for, in terms of restructured control, is the primary pitching moment control of the elevator on an aircraft. Therefore, thrust vectoring, which can produce pitching and yawing moments and X-, Y-, and Z- forces, will be one of the most versatile controls that can be implemented on an aircraft. Then, of course, there is the inlet which produces yawing moments and a lot of other kinds of effects as well.

All these different control devices, controlling vectors, if you want to call them that, exist now on aircraft. And this is only a partial list. By exploiting the secondary effects of these control devices, restructuring to maintain basic pitch and roll control seems almost always possible.

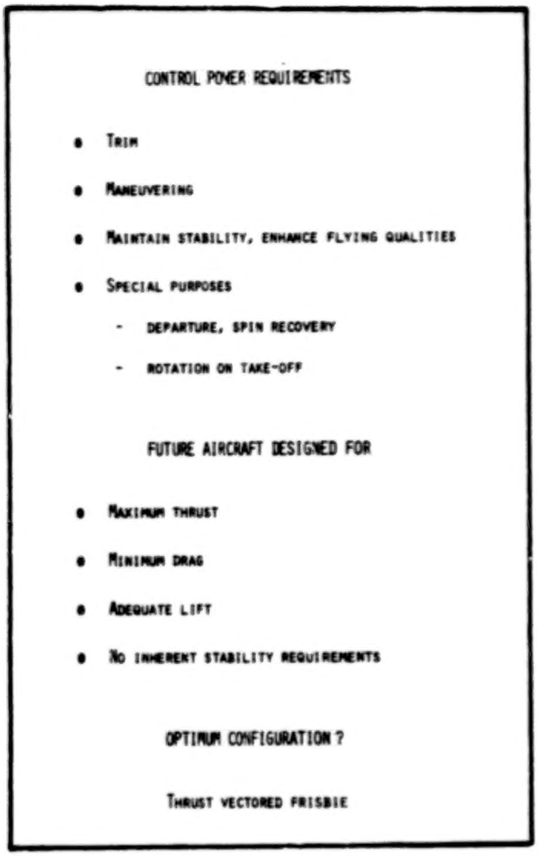


MULTIPLE MEANS OF GENERATING
FORCES, MOMENTS AVAILABLE

- LITTLE THOUGHT GIVEN TO RECONFIGURATION
- PROBABLE THAT MOST NEW CONFIGURATIONS CAN BE FLOWN WITH ALTERNATE EXISTING CONTROLS
    - AFTI-16
    - AFTI-111
    - X-29 (FORWARD SWEPT WING)
    - SHUTTLE
    - F-18
- VEHICLES NOT CONFIGURED FOR REDUNDANCY OF CONTROLS
- AIRCRAFT CONTROL SYSTEMS NOT DESIGNED TO CONSIDER MULTIPLE USE OF EXISTING CONTROLS

    I.E. ROLL AIRCRAFT 90°, USE RUDDER FOR PITCH CONTROL

As far as the design of the aircraft is concerned, to the best of my knowledge, essentially little thought is given to restructure in the design of these aircraft controls. And it is probable that most new configuration aircraft can be flown with alternate existing controls. Some examples of such aircraft are the AFTI-16, the AFTI-111, the X-29, the Shuttle, although this is less likely, and the F-18 that have a redundant set of controls. These aircraft have not a redundant, but a superfluous set of controls, and to the best of my knowledge, except for the F-16's CCV program, the restructurable control potential was not really considered. Thus this is virgin territory that we are talking about. It is not only a virgin territory, but a territory that is expanding and is more likely to be successful than many others I have heard of in the recent past. Today's aircraft are not configured for redundancy of controls. Also, aircraft control systems are not designed to consider multiple use of existing controls. For instance, if we consider the L-1011 that got caught with its elevator hung up, the pilot could have provided pitching moment by rolling the aircraft ninety degrees and then using the rudder, taking advantage of the Euler angle type of situation in which airplanes fly.



CONTROL POWER REQUIREMENTS

- Trim
- Maneuvering
- Maintain stability, enhance flying qualities
- Special purposes
    - departure, spin recovery
    - rotation on take-off

FUTURE AIRCRAFT DESIGNED FOR

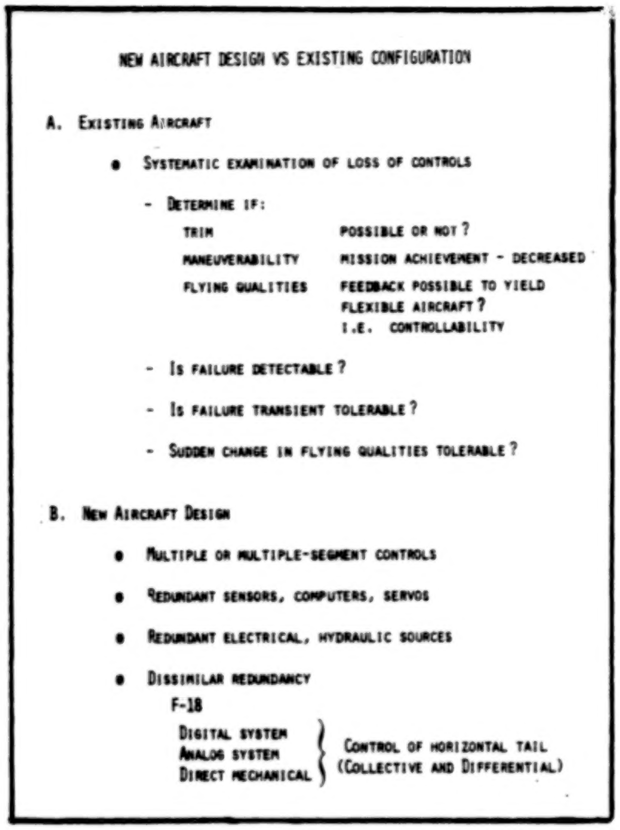
- Maximum thrust
- Minimum drag
- Adequate lift
- No inherent stability requirements

OPTIMUM CONFIGURATION ?

Thrust vectored Frisbie

Let us now consider control power requirements. Usually, control surfaces are sized for several reasons. Fundamentally there is trim, which is of prime importance. However, one must also have additional control power to maneuver the airplane, and that is of considerable interest to the Air Force. You also need some control power for feedback, if you are going to use it, for the purposes of maintaining stability and enhancing flying qualities. And let us face it, there are only two reasons why you use feedback on an aircraft: one is to maintain stability and the other is to enhance the flying qualities. Flying qualities are everything. They define the criteria of why you use flight control systems at all. So, if you do not have flying qualities as your criteria, you could be in big trouble. Flying qualities are defined by MIL-F-8785 B,C, which represent the only experimentally verified data essentially in existence today. You have spinoff, or alternate criteria, such as C*, which were generated analytically, but were never really experimentally verified in flight.

Future aircraft are going to be designed for maximum thrust, minimum drag, adequate lift, and no inherent stability requirements. Alright, what does that amount to? The optimum configuration of future aircraft amounts to a thrust vectored Frisbie, because a Frisbie has the maximum L/D that you could possibly ask for--a flying saucer. As long as you have the lift, the thrust, and lots of control power, you do not care what the airplane really looks like geometrically. So all the science fiction of the flying saucer is not that bad. From a flight-control point of view that is the optimum alternative, but obviously it cannot be achieved.



NEW AIRCRAFT DESIGN VS EXISTING CONFIGURATION

A. Existing Aircraft

- Systematic examination of loss of controls
  - Determine if:

TRIM	POSSIBLE OR NOT ?
MANEUVERABILITY	MISSION ACHIEVEMENT - DECREASED
FLYING QUALITIES	FEEDBACK POSSIBLE TO YIELD FLEXIBLE AIRCRAFT ? I.E. CONTROLLABILITY

  - Is failure detectable ?
  - Is failure transient tolerable ?
  - Sudden change in flying qualities tolerable ?

B. New Aircraft Design

- Multiple or multiple-segment controls
- Redundant sensors, computers, servos
- Redundant electrical, hydraulic sources
- Dissimilar redundancy

F-18

Digital system
Analog system
Direct mechanical

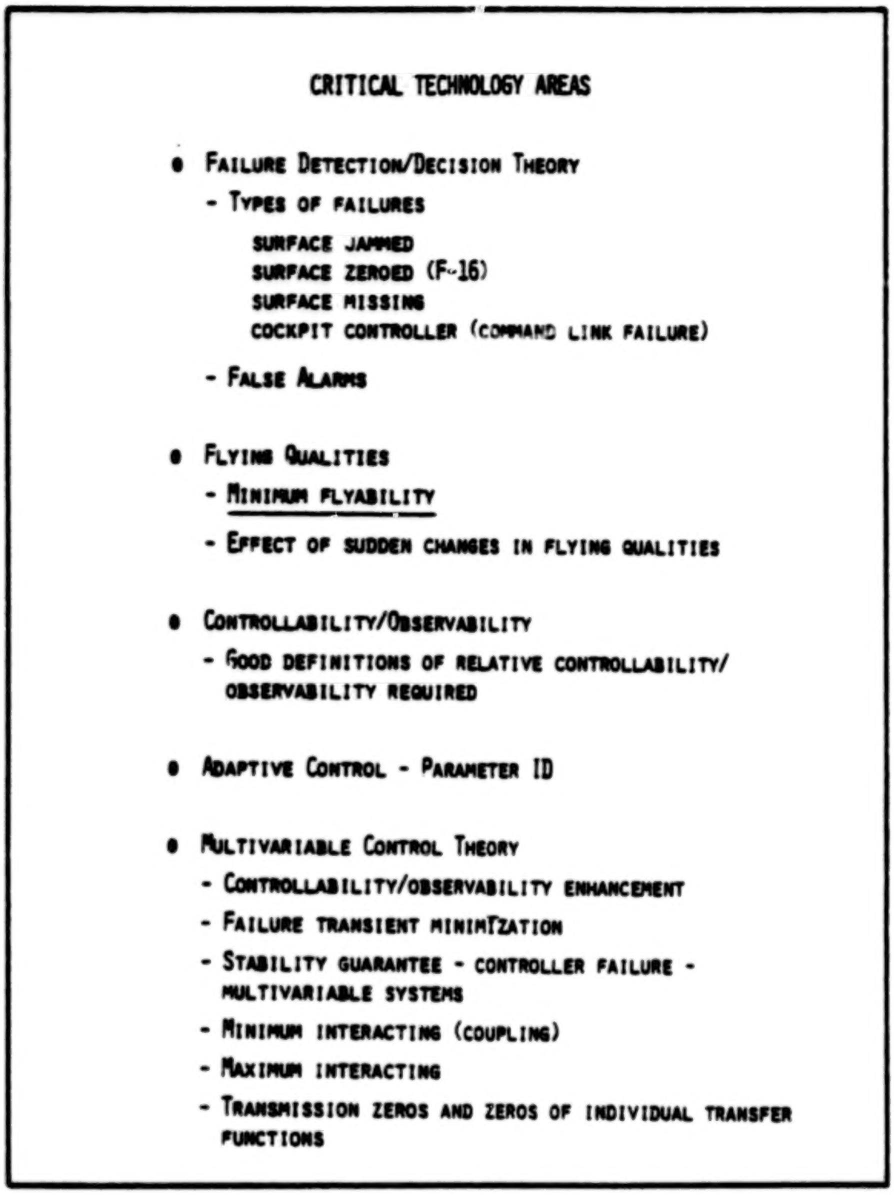
Control of horizontal tail
(Collective and Differential)

There are two ways we can look at this particular program: one has to do with existing aircraft and the other has to do with new aircraft design. I think that they represent two important, but significantly different, research objectives that a restructurable controls program might take.

For existing aircraft, one approach would be to take an existing aircraft, such as an F-18 or the AFTI-16, and conduct a systematic examination of the loss of the different controls. By systematic I mean examining the different ways in which you can lose a control. For example, it could break off, it could hang up, it could go maximum deflection, or it could tear. And then determine if it is possible to trim throughout; and this, of course, is a function of flight envelope, or flight condition. How about maneuverability? Can you achieve the mission with the excess control power you have available above and beyond trim, or not? And then of course, what are the flying qualities? Because for the Air Force, if it is an F-16 or an unstable configuration, you have got to provide stability for this aircraft. So you look at some things like controllability of the vehicle. That is, controllability, not only in the classic sense that Mike Athans referred to, but also in terms of trim and control power left for maneuver--the static as well as the dynamic controllability of the aircraft. And then, of course, you have to ask some additional questions. Is the failure detectable? It may not be. If you have no failure transients associated with a failure, which is possible if you are flying in trim then you may not detect it unless, of course, you have a sensor on the surface. That may be, but if the surface does not move, then you have no way of detecting a failure.

But that might not be so bad. If you are in trim and you have a failure, then detecting it may serve no purpose at that particular time. On the other hand, if the failure occurs at other times in the flight range when you are out of trim, then you can have significant failure transients, particularly if the failure results from an unstable configuration, like the F-16, for instance. Another factor to be considered concerns the sudden change in flying qualities. Of course, first of all you have to ask the question, can you maintain the same flying qualities with an alternate control surface? Perhaps you can; perhaps you cannot. If you can, you may have so little control power left over that you cannot maneuver. So you may not want to maintain the same flying qualities before and after the failure.

In the new aircraft design one has to consider such things as multiple, or multiple-segment controls; that is, the elevator, rudder, and aileron divided into several segments. In addition, one has to consider redundant sensors and redundant electrical and hydraulic sources. For example, the F-16 has an electrical power system which is not redundant but triple string. In other words, you have to have essentially three failures occurring before you lose all electrical power. An example of dissimilar redundancy is the F-18, which has a digital control system, an analog system, and a backup direct mechanical system. And the mechanical system, I understand, is to be removed after awhile when they determine that reliability is satisfactory with the digital and analog systems. But as far as redundancy applied to control systems is concerned, the dissimilar redundancy is more important than the similar redundancy of, say, the F-16. Now there is a quad-analog type of feedback system where you could have a failure that commonly affects each of the feedback paths.



CRITICAL TECHNOLOGY AREAS

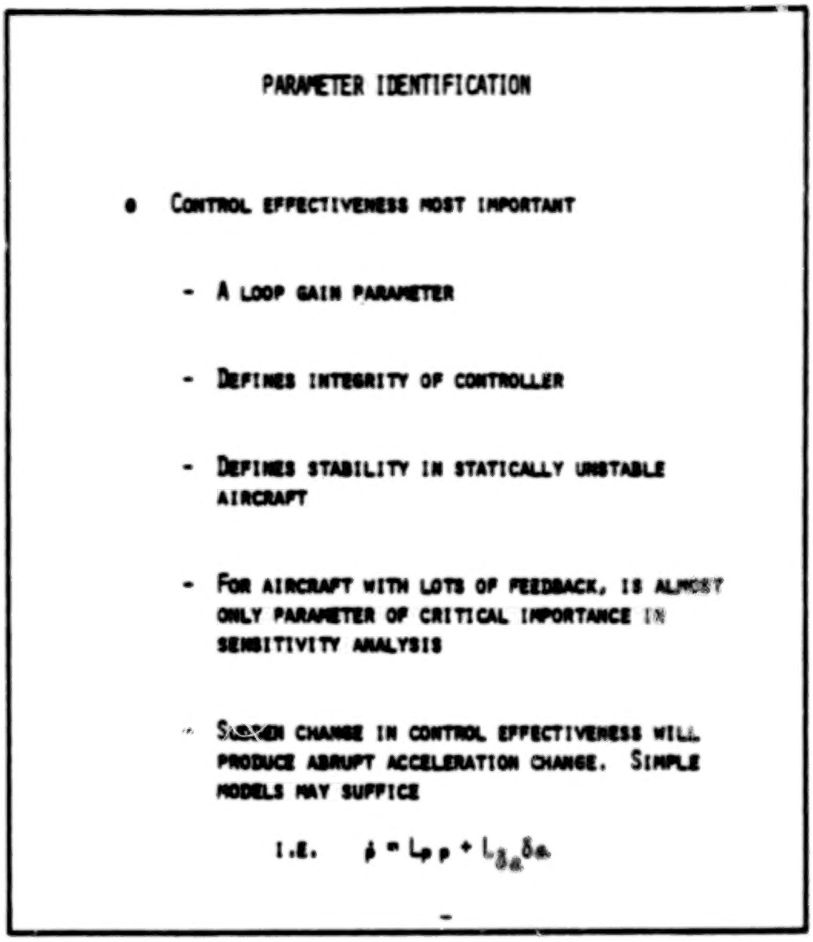
- FAILURE DETECTION/DECISION THEORY
  - TYPES OF FAILURES
    - SURFACE JAMMED
    - SURFACE ZEROED (F-16)
    - SURFACE MISSING
    - COCKPIT CONTROLLER (COMMAND LINK FAILURE)
  - FALSE ALARMS
- FLYING QUALITIES
  - MINIMUM FLYABILITY
  - EFFECT OF SUDDEN CHANGES IN FLYING QUALITIES
- CONTROLLABILITY/OBSERVABILITY
  - GOOD DEFINITIONS OF RELATIVE CONTROLLABILITY/ OBSERVABILITY REQUIRED
- ADAPTIVE CONTROL - PARAMETER ID
- MULTIVARIABLE CONTROL THEORY
  - CONTROLLABILITY/OBSERVABILITY ENHANCEMENT
  - FAILURE TRANSIENT MINIMIZATION
  - STABILITY GUARANTEE - CONTROLLER FAILURE - MULTIVARIABLE SYSTEMS
  - MINIMUM INTERACTING (COUPLING)
  - MAXIMUM INTERACTING
  - TRANSMISSION ZEROS AND ZEROS OF INDIVIDUAL TRANSFER FUNCTIONS

Critical technology areas involve failure detection and decision theory. We have to consider several different types of failures, of course. We cannot just say a surface failed. That does not really mean anything to a real airplane. The surface can be jammed. Alternatively, the surface can be zeroed like in the F-16 where it is spring-loaded, and in case of a failure of the flight control system, that surface is just zeroed or taken back to some original fixed position. What is done for this alternative is to select that position that represents trim position over the widest portion of the flight range, and that is the area in which the airplane flies most often, which is high subsonic. Nevertheless, it is still an unstable aircraft when you lose your feedback. You have a step input due to the fact that the elevator is returned to some original neutral position. The aircraft is highly unstable (pole in the right half plane, if you like) and they have had accidents which, in one case, produced a hard noseover and they lost the pilot. In another case they produced a positive G, a pulloff, where the pilot was able to eject. But the point is that, depending on where that surface is with respect to trim when the failure occurs, you could have either a pushover or a pulloff and these are very high magnitude maneuvers. That, I would consider, is a very significant type of control system failure, although it does not involve a surface as such. There should still be some way to provide an emergency situation that would enable the pilot to get out of the airplane; even if he is over enemy territory, it is better to get out. Now, false alarms are really bad news. If you have a false alarm or if you make an improper decision once in these types of systems, then the pilots may never use the system again. This is, however, the psychology of pilots and they need only one really bad experience before, for all practical purposes, you are out of business. So you have to be very careful.

As far as flying qualities are concerned, there are two areas, I think, that require more research, more investigation, and better definition: one is the minimum flyability as far as aircraft are concerned, not only with respect to experienced test pilots but also with respect to the line pilots, and the other is the effect of sudden changes in flying qualities of the aircraft. It is what STI's McRuer would like to try to arrange: a graceful degradation of flying qualities. But unfortunately the loss of the control surface is not going to be very graceful.

Then, of course, there is the area of adaptive control and parameter identification. And that is about as far as I want to discuss it.

Now as far as some of the more theoretical aspects, you can consider multivariable control theory that was discussed this morning by Mike Athans. I think this contains a wealth of the type of information that is needed and defines many of the areas in which theoretical as well as applied research is required, such as enhancement of control system design for improved observability and controllability, and for coupling different surfaces together. Mathematically speaking, controllability and observability are more or less absolute types of definitions. What is really needed is a better definition of relative controllability. That would be quite helpful. Failure transient minimization--how do you minimize the transients that occur? You might produce a failure that would generate a transient more gradually rather than more suddenly. How do you guarantee stability in case of a controller failure when you are feeding back to many different controllers at the same time? This is a difficult problem as referred to in the work by Ackerman. There are considerable problems having to do with that because essentially when we go through multivariable control system designs, there are problems maintaining a minimum phase for some of the individual transfer functions. Now the zeros of individual transfer functions are often just as important to the pilot as the poles in the system, the eigenvalues. And they have to be watched very carefully in the multivariable control system design to avoid the introduction of closed loop, nonminimum phase responses. Then, also, there are good theoretical areas in minimum interacting or decoupling, and also in maximum interacting or coupling. Both of those areas are just as important with respect to each other, because they are obviously closely related and because the emphasis has been on minimum interacting types of systems. Much more research is required in how to get these systems to interact maximally. The design should be such, if possible, that each controller adds to the total controllability of the system, rather than have controllers effectively oppose each other.

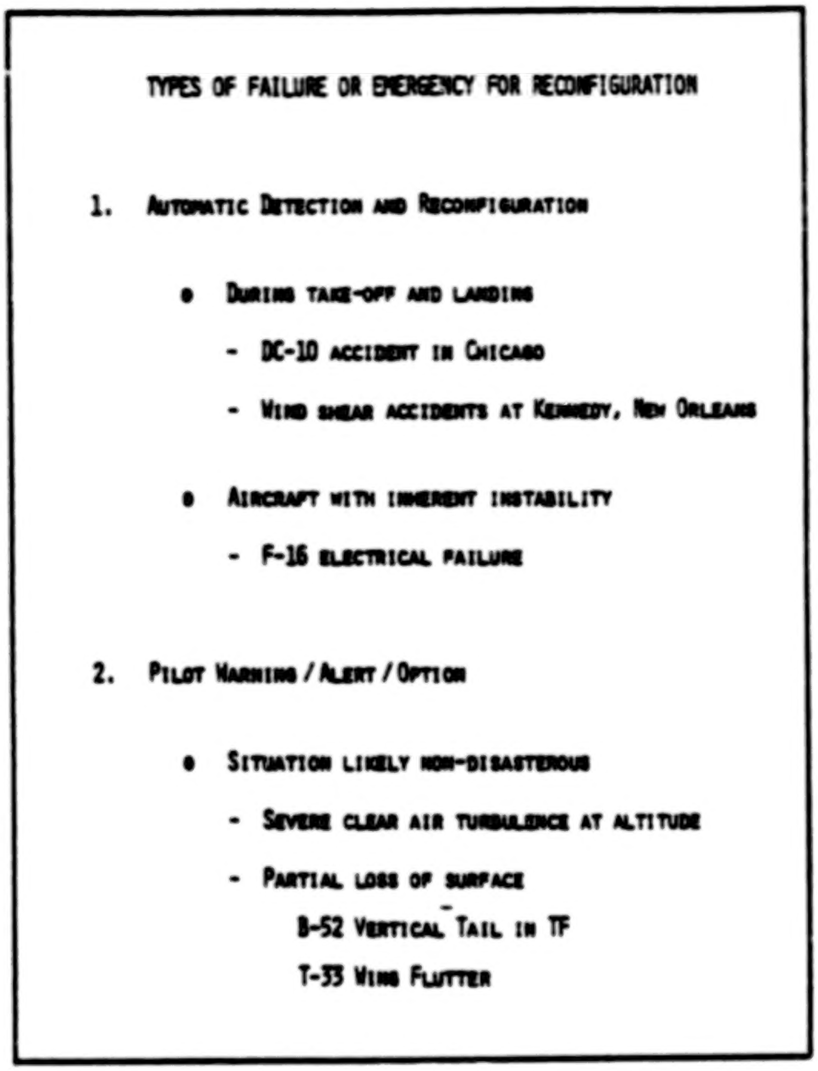


PARAMETER IDENTIFICATION

- CONTROL EFFECTIVENESS MOST IMPORTANT
  - A LOOP GAIN PARAMETER
  - DEFINES INTEGRITY OF CONTROLLER
  - DEFINES STABILITY IN STATICALLY UNSTABLE AIRCRAFT
  - FOR AIRCRAFT WITH LOTS OF FEEDBACK, IS ALMOST ONLY PARAMETER OF CRITICAL IMPORTANCE IN SENSITIVITY ANALYSIS
  - SUDDEN CHANGE IN CONTROL EFFECTIVENESS WILL PRODUCE ABRUPT ACCELERATION CHANGE. SIMPLE MODELS MAY SUFFICE

I.E. $\dot{p} = L_p p + L_{\delta_a} \delta_a$

Right after saying that I was not going to discuss parameter identification, I have a viewgraph entitled "Parameter Identification." Obviously, what we are looking for in parameter identification is control effectiveness. And also I might add control power, but control effectiveness is the most important. This is a loop-gain parameter in the general sense. It defines the integrity of the controller. It also defines stability in statically unstable aircraft, as you have feedback on stabilized aircraft. For aircraft with lots of feedback, it is almost the only parameter of crucial importance if sensitivity develops as an issue. That is not quite a true statement, obviously, but let us say that it is the dominant parameter. Sudden changes in control effectiveness will produce abrupt acceleration change. For that reason, simple models may suffice. For example, for the rolling degree of freedom, the equation given here may be enough for the purpose of trying to find the integrity of the controller. Or it may not be enough. But at least it is probably the place to start.



TYPES OF FAILURE OR EMERGENCY FOR RECONFIGURATION

1. Automatic Detection and Reconfiguration
    - During take-off and landing
        - DC-10 accident in Chicago
        - Wind shear accidents at Kennedy, New Orleans
    - Aircraft with inherent instability
        - F-16 electrical failure
2. Pilot Warning / Alert / Option
    - Situation likely non-disasterous
        - Severe clear air turbulence at altitude
        - Partial loss of surface

          B-52 Vertical Tail in TF

          T-33 Wing Flutter

Failure essentially has to be defined. What do we mean by a failure? Failure can be a physical failure such as a loss of a surface. However, another type of failure, which I would like to introduce, is the failure caused by external disturbances that cannot be detected or even controlled by the pilot.

We have two types of failures that should be considered. One type includes failures that require automatic detection and restructure, as far as trimming the airplane is concerned, independently of the pilot. Most of these can be defined during takeoff and landing, such as the one that caused the DC-10 accident in Chicago and windshear accidents at Kennedy, New Orleans, and other places. These are catastrophic failures where the pilot has very little, if any, time to react. First of all he has to recognize the problem and then he has to react to the problem. There is no doubt, for instance, that wind shears can essentially be accommodated with an automatic control system, if the control system is designed to recognize the shear and act accordingly to get the pilot to fly out of it. Obviously, because of the accidents, the pilot cannot always do it. Other failures in this category involve aircraft with inherent instabilities. In these aircraft, when a failure occurs very suddenly, the effect can be so castastrophic in terms of a maneuver that, in order to keep the pilot aware of what happened, some method of automatic trim should be required.

Now, the other type of failures includes those in which we might consider just warning the pilot or alerting him. These are essentially high altitude types of phenomena, such as severe clear air turbulence at high altitude. These are not disastrous, but still clear air turbulence can produce problems. It produced, for instance, the famous B52 vertical tail incident during terrain following. I do not know if you recall that, but they lost two-thirds of the vertical tail surface during terrain following due to turbulence. There may have been other things wrong. And there is also the problem of the T-33 wing flutter type of accident that we had and I referred to earlier. These are at least two categories of kinds of failure that one might consider doing something about.

Now, as a conclusion, we can consider what type of controller we might like--a universal type of controller, if we had an option on how to do it. One suggestion, or one thing I might put up to you, is a split aileron type of device. Because depending on where this device is located on the wing, you could control up to all six degrees of motion. In other words, the aileron is split so that it acts in a clamshell open-and-close mode as well as the deflection up-and-down mode. What will it give you? It can give you roll, of course, acting as conventional differential ailerons. It can give you direct lift acting directly, or pitch depending on where they are located. If they are located near the wing tip of a swept wing aircraft, then they can give you as much pitching moment as direct lift, or both. Or you can use the collective ailerons with the elevator to give you both pitching moment and direct lift forces. Operating in the clamshell mode, the open-and-close mode, you can get direct modulation of the X-force. Or if you operate the clamshells differentially, then you will get a yawing moment for the aircraft. And if you operate the split ailerons differentially in conjunction with the rudder, then you can get a direct side force on the aircraft. So depending upon how this particular type of device is configured and where it is located on the wing or wherever on the aircraft, you can have the possibiltiy of getting control forces and moments along and about all three axes of the aircraft. So, I am saying that this is merely a simple example to show that there is a lot yet that can be done in terms of enhancing the controllability of aircraft for the purpose of restructuring.

A REVIEW OF SYSTEM IDENTIFICATION METHODS APPLIED TO AIRCRAFT

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Introductory Remarks

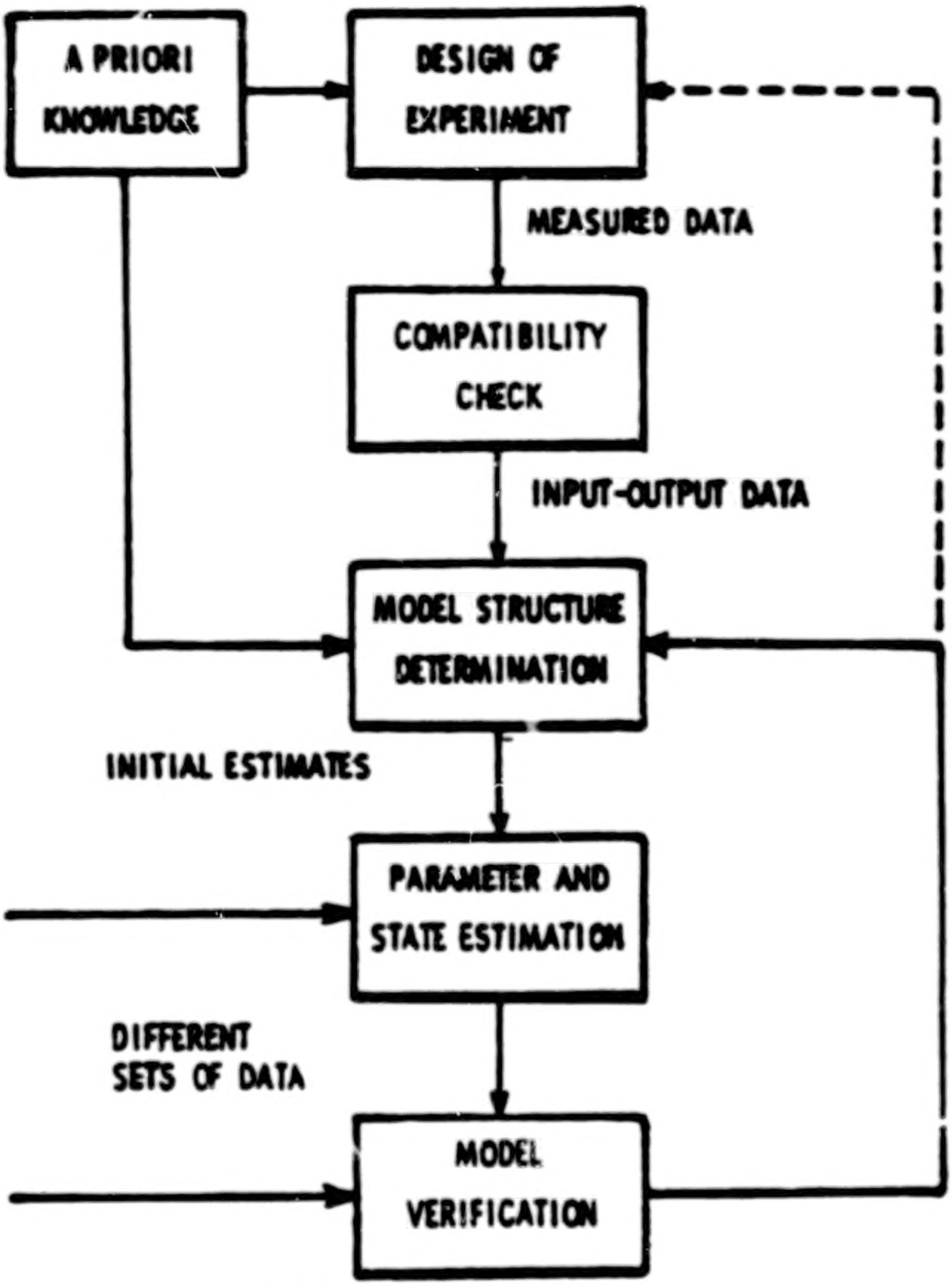
The topic that I will address at this workshop is a review of available system identification methods that may be applied to obtain the model of an airplane based upon the flight test data.

IDENTIFICATION
(DEFINITION BY ZADEH)

IDENTIFICATION IS THE DETERMINATION, ON THE BASIS OF INPUT AND OUTPUT, OF A SYSTEM WITHIN A SPECIFIED CLASS OF SYSTEMS, TO WHICH THE SYSTEM UNDER TEST IS EQUIVALENT.

The definition of identification is based upon the Zadeh formulation. This formulation says that identification is the determination, on the basis of input and output, of a system within a specified class of systems, to which the system under test is equivalent.

Basically, the definition means that for system identification one must have these three items: the input and output data, a specified class of systems, and finally some set of criteria which will tell how close the model is to the actual system under test.



BLOCK SCHEME OF AIRPLANE IDENTIFICATION

A PRIORI KNOWLEDGE
DESIGN OF EXPERIMENT
MEASURED DATA
COMPATIBILITY CHECK
INPUT-OUTPUT DATA
MODEL STRUCTURE DETERMINATION
INITIAL ESTIMATES
PARAMETER AND STATE ESTIMATION
DIFFERENT SETS OF DATA
MODEL VERIFICATION

The system identification is part of the overall study for obtaining the model of an airplane from flight test data and this is an outline of the flow diagram of the process.

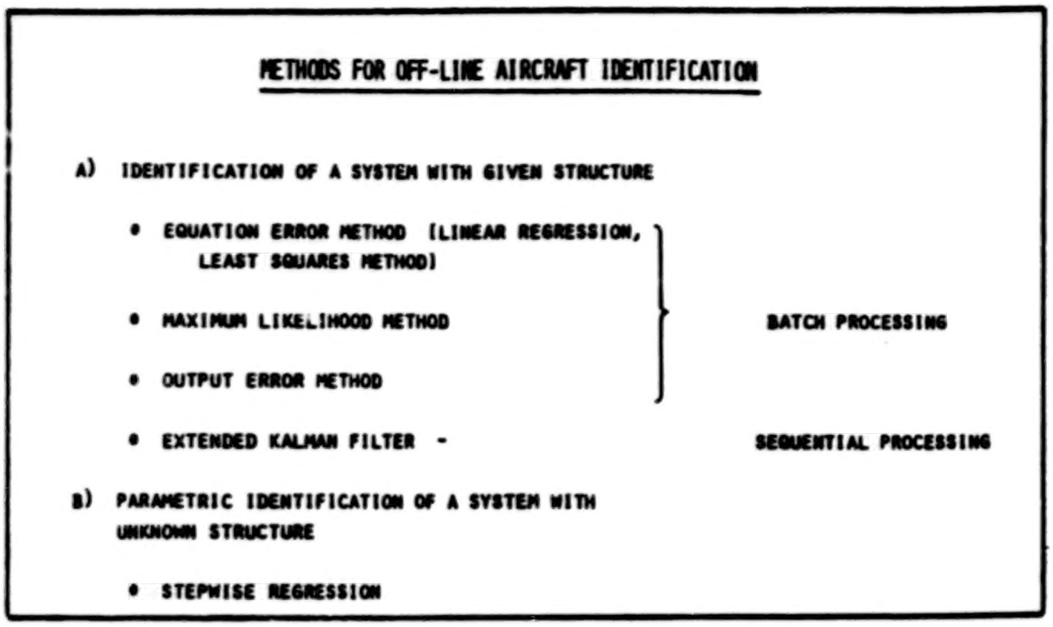
First of all we start with some kind of a priori knowledge which is used twofold: first of all it is used in the design of an experiment, and then in the model structure determination. Basically what I mean by design of an experiment is just how to find what would be the best input for good excitation of the transient motion of an airplane. There are several approaches to this problem: either just a simple engineering judgment or some semi-empirical estimation of the inputs based on a selected criterion that you want to achieve; either the estimates with the lowest variance, or the estimates which give you the responses closest to the measurements, and so forth. After designing and executing the experiment, you have a set of measured data, usually in terms of time histories of input and output variables.

Then there is a so-called compatibility check. The purpose of this is essentially to find what kind of bias errors are in your measured data, and, if there are any, how to remove them. Usually we are talking about the bias errors in terms of the constant offsets or scale errors. In this box also, we might reconstruct some variables which may be missing from the measurements. For example, sometimes it might happen that we cannot measure the angle of attack. But, using the measurements of the angular velocities and accelerations, we can reconstruct the time history of the angle attack.

After the compatibility check it can be assumed that the measured responses are essentially true values of these variables which are corrupted by the measurement noise, because all the possible bias errors have already been removed.

The next step is indicated here in two blocks, i.e., the model structure determination, and parameter and state estimation. In some techniques all these steps can be executed at the same time. If we know, or if we assume that the model structure is known, the identification task is reduced to parameter and state estimation.

Finally, the last and probably the most difficult part of the whole procedure is the model verification. We would like to have estimates of the parameters which do have physical values and we would also like the estimates of the model with good prediction capabilities.



METHODS FOR OFF-LINE AIRCRAFT IDENTIFICATION

A) IDENTIFICATION OF A SYSTEM WITH GIVEN STRUCTURE

- EQUATION ERROR METHOD (LINEAR REGRESSION, LEAST SQUARES METHOD)
- MAXIMUM LIKELIHOOD METHOD
- OUTPUT ERROR METHOD

} BATCH PROCESSING

- EXTENDED KALMAN FILTER - SEQUENTIAL PROCESSING

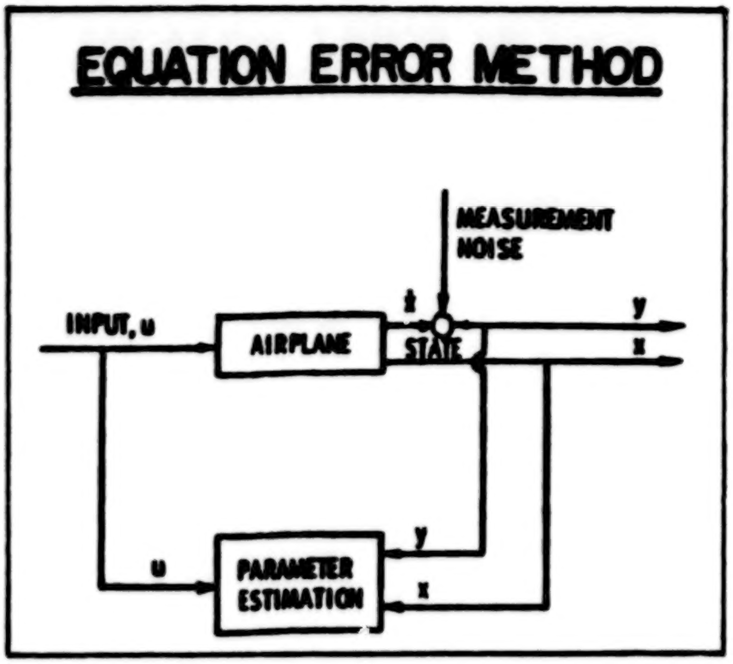
B) PARAMETRIC IDENTIFICATION OF A SYSTEM WITH UNKNOWN STRUCTURE

- STEPWISE REGRESSION

I would like to talk very briefly about various techniques for parameter estimation. I mentioned one technique which can estimate the model structure based upon the flight test data, and all of these techniques shown in the next few viewgraphs are off-line techniques. Here is a very brief summary of these techniques. They are divided into two groups: identification of a system with a given structure and parametric identification of a system with an unknown structure. I will address only the former in this viewgraph.

The methods for identification of a system with given structure essentially estimate the parameters from the set of input and output data. The first group of these techniques are the so-called equation error methods, or they are also known as linear regression or least square methods. The names tell you what kind of techniques these are. The second technique is the famous maximum likelihood method. The third technique is the output error method which can be considered as a simplified version of the maximum likelihood technique. And finally the fourth technique is the extended Kalman filter. The first three techniques are usually used in batch processing mode whereas the fourth one is a sequential method.

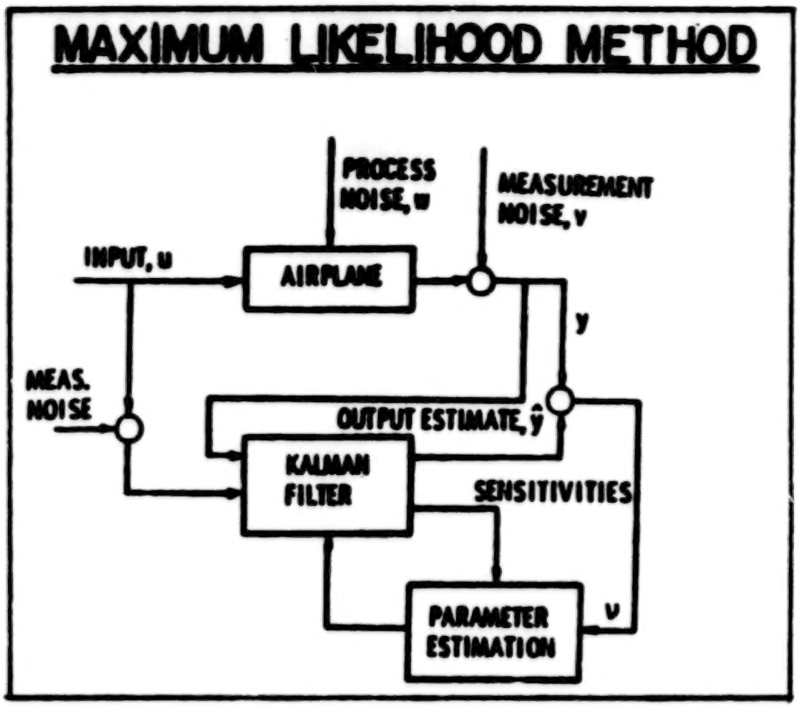
The equation error methods provide the direct estimates of the parameters. The recursive techniques start with some estimates and iterate to the final parameter estimates.



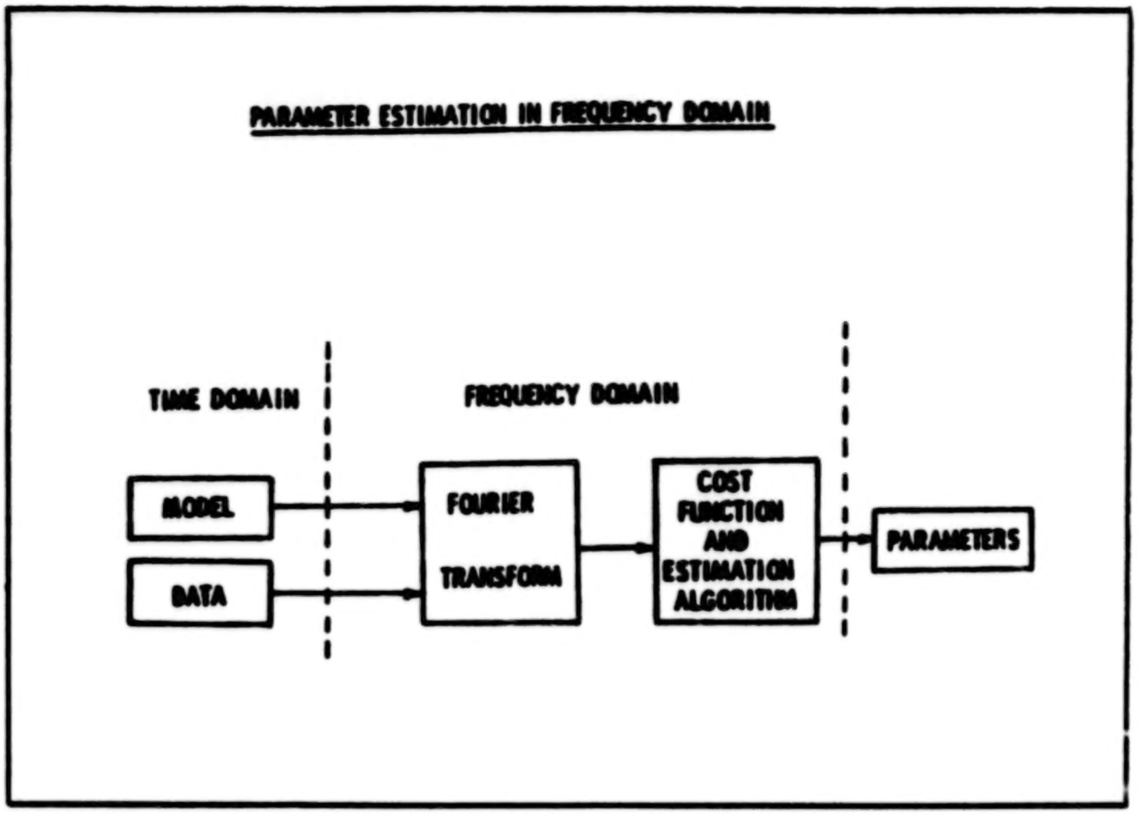
I will outline, very briefly, how these techniques work just using this simple flow diagram without any mathematics. For the equation error method, the airplane response is excited by input u. We measure the state variables and also the derivatives of the states, and we assume that only the measured data of these states are corrupted by measurement noise. All the information about u, $\dot{x}$, and x is used for the parameter estimation, where the $\dot{x}$ (corrupted by noise) is called y and serves as the dependent variable in the regression equation, and x and u serve as the independent variables in the same equation.

There are disadvantages with this technique. First you must know all these variables from the measurements. Secondly, according to the theory, the estimates are biased because in reality there is always some measurement noise in the input and state variables.

The advantage of the equation error method is that it is a very simple technique for obtaining estimates. The technique is applied to each equation of motion separately which results in a small number of unknown parameters.


MAXIMUM LIKELIHOOD METHOD
PROCESS NOISE, w
MEASUREMENT NOISE, v
INPUT, u
AIRPLANE
y
MEAS. NOISE
OUTPUT ESTIMATE, $\hat{y}$
KALMAN FILTER
SENSITIVITIES
PARAMETER ESTIMATION
ν

Let us go on to describe the maximum likelihood technique. As indicated in this viewgraph, this technique assumes again that there is an excitation of the system by an input and that the system response is measured. Both the input variables and the output variables are corrupted by the measurement noise. In addition the airplane is disturbed by external disturbances, such as turbulence. Now, the measurements are used in the Kalman filter which has fixed parameters and which estimates the response of the plant and also gives the sensitivities for the parameter estimation. Once the parameters are estimated, the Kalman filter parameters are updated and the whole procedure is repeated. Before the procedure starts, it is assumed that we know the estimates of the parameters. After the first iteration, these parameters are updated and the procedure is repeated. If the assumption is made that there is no noise in the input and that there is no process noise, then the maximum likelihood method is reduced to the so-called output error technique.


PARAMETER ESTIMATION IN FREQUENCY DOMAIN

TIME DOMAIN
FREQUENCY DOMAIN
MODEL
DATA
FOURIER TRANSFORM
COST FUNCTION AND ESTIMATION ALGORITHM
PARAMETERS

Very often then, when describing these methods we are speaking in terms of the time domain. It can be shown that both techniques can be transferred into the frequency domain. The Fourier transform is applied both to the model and the data. The output of these transformations are input to a cost function which is formulated in the frequency domain. Then the final parameter estimates are obtained.

The frequency domain approach can be considered as a complementary technique to those in the time domain. It can be shown that all these techniques, output error, maximum likelihood, and equation error, can be formulated in the frequency domain.

EXTENDED KALMAN FILTER

GIVEN SYSTEM

$$\dot{x}(t) = \theta \; x(t) + u(t) + w(t)$$

AUGMENTED SYSTEM

$$\dot{x}(t) = \theta \; x(t) + u(t) + w(t)$$

$$\dot{\theta}(t) = 0$$

OR

$$\dot{x}_A(t) = f\left[x_A(t), \; u(t)\right] + w_A(t)$$

WHERE

$$\dot{x}_A^T(t) = \left[x(t) \; , \; \theta(t)\right]$$

This viewgraph shows the application of the extended Kalman filter to a very simple system. We have a system with only one parameter, and we want to estimate both the state variables and this parameter at the same time. The procedure is to define a so-called augmented system, where the augmented state variable vector includes both the state variables and the unknown parameter. Then, the Kalman filter is applied to this system with the augmented state variable.

AIRCRAFT EQUATIONS OF MOTION

A) GENERAL EQUATIONS WITH LINEAR AERODYNAMIC FUNCTIONS

$$m\left(\frac{d\vec{V}}{dt} + \vec{\omega} \times \vec{V}\right) = \vec{F}_G + \vec{F}(\vec{V}, \vec{\omega}, \vec{\delta})$$

$$\frac{d\vec{H}}{dt} + \vec{\omega} \times \vec{H} = \vec{M}(\vec{V}, \vec{\omega}, \vec{\delta})$$

$$F = F_0 + \frac{\partial F}{\partial V} V + \frac{\partial F}{\partial \omega} \Delta\omega + \frac{\partial F}{\partial \delta} \Delta\delta$$

$$M = M_0 + \frac{\partial M}{\partial V} V + \frac{\partial M}{\partial \omega} \Delta\omega + \frac{\partial M}{\partial \delta} \Delta\delta$$

B) LINEARIZED EQUATIONS

$$\dot{x} = Ax + Bu$$

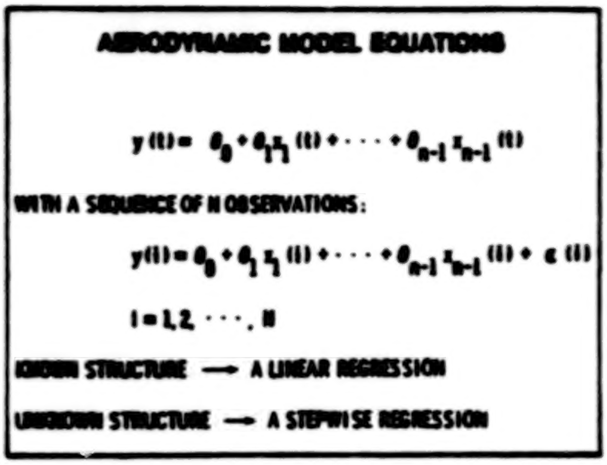
WHERE

$$x^T = [\Delta u, \Delta w, \Delta q] \quad \text{or} \quad [\Delta v, \Delta p, \Delta r]$$

$$u^T = \delta_e \quad \text{or} \quad [\delta_a, \delta_r]$$

The second type of method is the technique for parameter identification of an aircraft with unknown structure. So far only the so-called step-wise regression technique has been applied for this purpose. I would like to talk about it a little bit more because it is a relatively new approach to aircraft parameter identification.

We begin with the aircraft equations of motion which are given by these two vector equations shown. These equations are based upon the dynamics of the rigid body. Essentially they describe the equilibrium between the inertia forces, the gravity forces, and the aerodynamic forces, as well as the equilibrium between the inertia moments and the aerodynamic moments acting upon the airplane. In the previous schemes that I have been talking about, typically these general equations of motion are used. Usually a linear relationship between the forces and between the moments is assumed as indicated here by this Taylor series expansion in which only the linear terms are taken into account. A second possibility for this is simply to linearize the equations and thus remove the problems of expressions for the aerodynamic forces and moments acting on the airplane. This set of equations has then a very well known form. In this equation the state variables are either the longitudinal variables (Δu, Δw, Δq) or the lateral variables (Δv, Δp, Δr), and the control variables are the deflections of either the elevator or the aileron and rudder.



AERODYNAMIC MODEL EQUATIONS

$$y(t) = \theta_0 + \theta_1 x_1(t) + \cdots + \theta_{n-1} x_{n-1}(t)$$

WITH A SEQUENCE OF N OBSERVATIONS:

$$y(i) = \theta_0 + \theta_1 x_1(i) + \cdots + \theta_{n-1} x_{n-1}(i) + \varepsilon(i)$$

$$i = 1, 2, \cdots, N$$

KNOWN STRUCTURE ⟶ A LINEAR REGRESSION

UNKNOWN STRUCTURE ⟶ A STEPWISE REGRESSION

The aerodynamic equation can be written in the general form shown in this viewgraph where the y represents the aerodynamic coefficient and θ_0 represents the value of this coefficient which corresponds to the trimmed condition. The x_1, x_2, and so on represent the state variables, response variables, control variables, or the combination of these variables. Finally, the θ_1, θ_2, and so on are the unknown parameters.

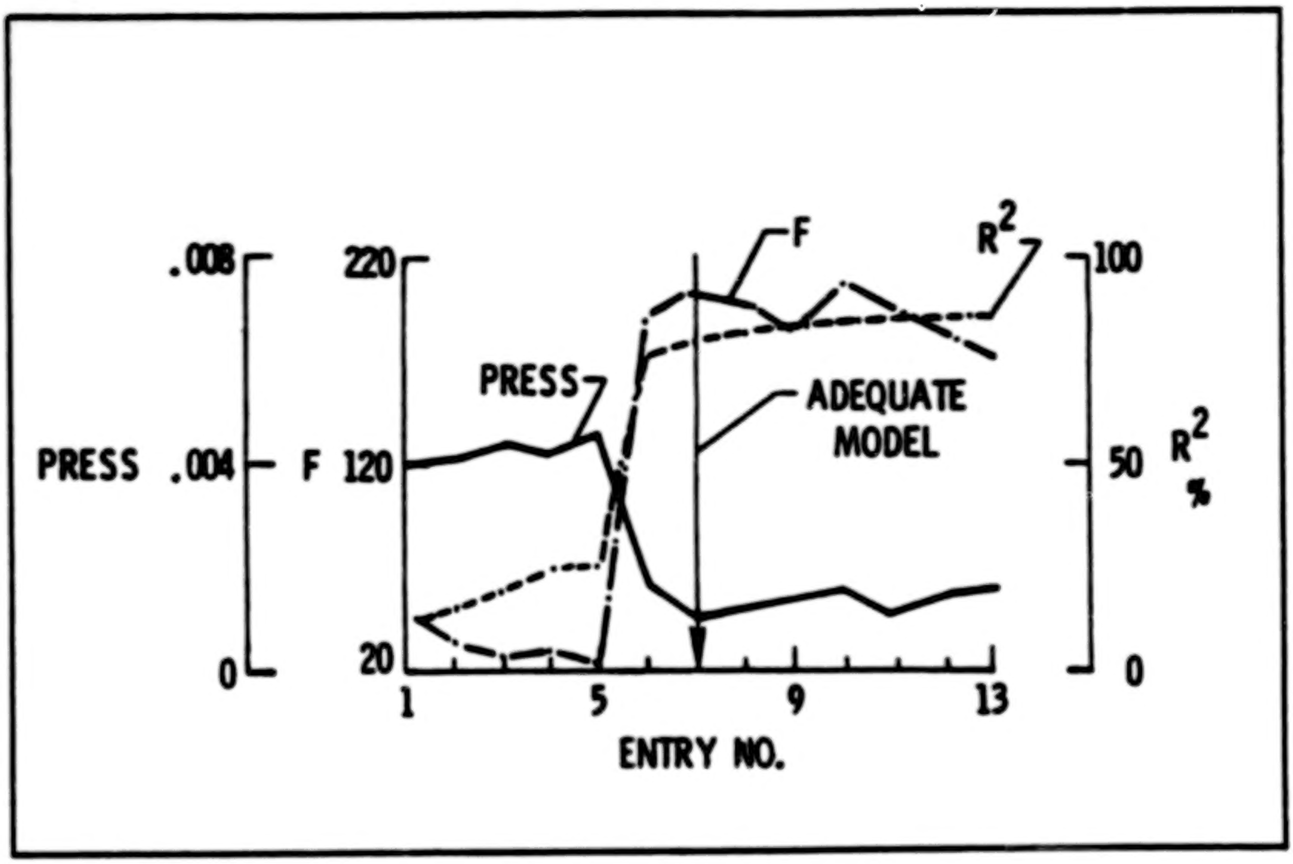
When we have a sequence of N observations we can substitute the measured values into the set of regression equations where ε represents the equation error. Now, there are two possible cases. I have already talked about the first one. We know the structure of this linear regression and the estimates are simply obtained by applying the least squares technique. In the second case we do not know what the optimal structure is, then we have to use the so-called stepwise regression.

Now let me say a few words about this technique itself. The technique starts with the postulation of all possible terms which might be included in the model. The technique selects the optimal subset from these by simply checking all these postulated terms and selecting the one variable which is mostly correlated with the dependent variable, y_i. Let us consider that this variable is x_j. Then the parameter θ_1 is estimated, and the model after the first step is simply θ_0 plus $\theta_1 x_1$. Then the procedure continues by checking the remaining terms in the postulated model and selecting the most significant one, and by estimating the parameter associated with the term selected. The technique also rechecks whether the terms selected before remain significant after bringing the new one into the model. This is some kind of model building. There is a certain criterion which tells you where you should stop the procedure, and which should result in an optimum model. I just included some kind of example that should give you the idea how this procedure works and what can be achieved by applying this procedure.

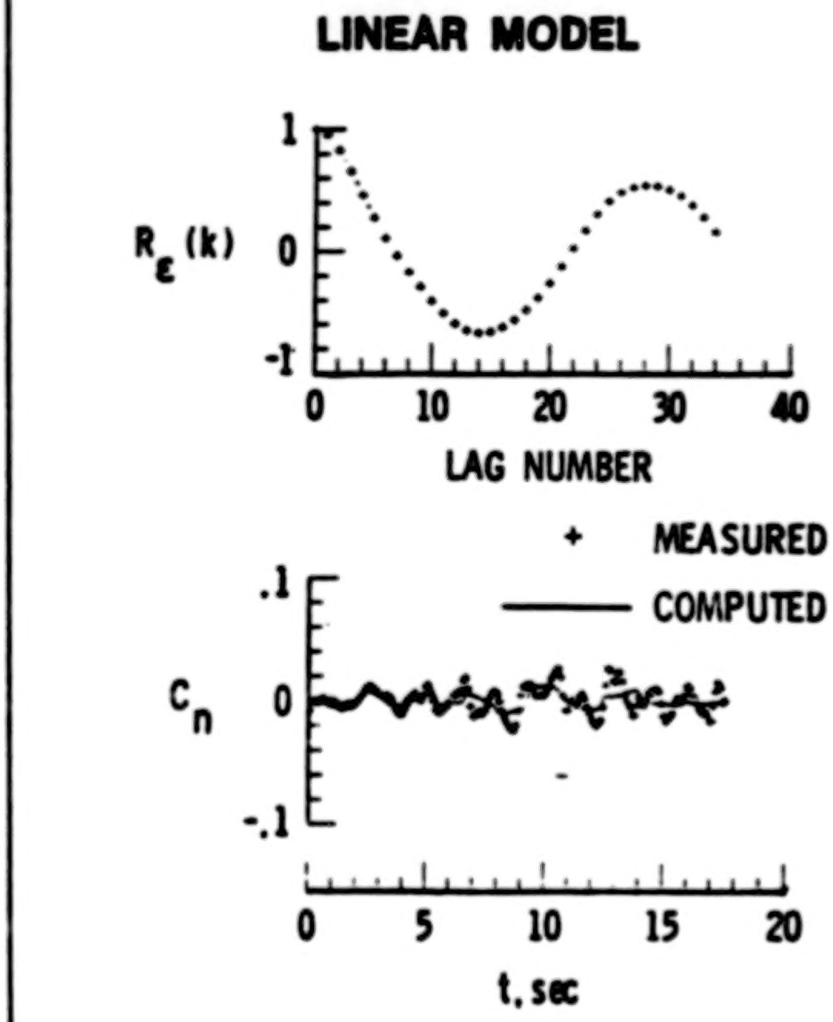
CRITERIA FOR THE SELECTION OF A PARSIMONIOUS MODEL

1. F - STATISTICS ⟶ THE RATIO (REGRESSION MEAN SQUARE) TO (RESIDUAL MEAN SQUARE)
2. PRESS ⟶ THE PREDICTION SUM OF SQUARES
3. R^2 ⟶ THE SQUARE MULTIPLE CORRELATION COEFFICIENT
4. ANALYSIS OF RESIDUALS

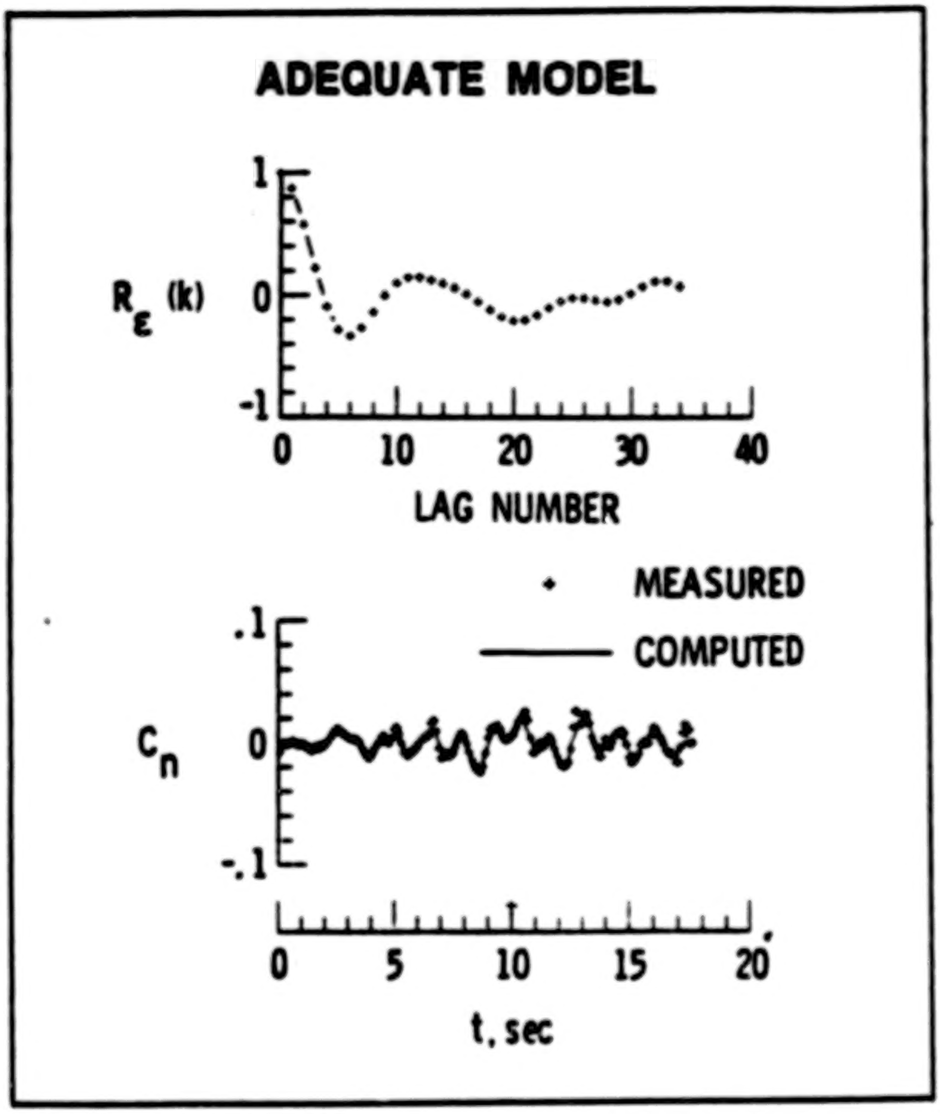
What is given here are various criteria for the selection of this optimal subset from the postulated terms in the model for any specific aerodynamic coefficient. These criteria are called Prediction Sum of Squares (PRESS), F-Statistic, and squared multiple correlation coefficient, (R^2). The PRESS tells us that its minimum value should give us the model with the best prediction capability. For the F criterion, the maximum values of the F-value should give us the set of the minimum number of parameters which best fit the model. And finally the R^2 tells us the percentage of the information explained by the model with various terms included.



The entry number means the number of terms included in the model. From what you can see here, the model building starts with the first step and goes to the fifth one. The PRESS criterion was very high. The F-criterion was very low. After bringing the next terms, as it was with the sixth term, there was some change in the PRESS criterion and sudden improvement in the F-criterion and also improvement in the R^2 term. The model at the seventh entry was the best model, or the optimum model, whatever you want to call it.



In this example this technique was applied to the yawing moment coefficient and it shows how the fit to the data looked after 5 terms are included in the model. The crosses are the measured data and the thin line is the prediction of the yawing moment coefficient. You can see that it is a very poor fit. In this case all the linear terms are included in the model. This was also reflected in the autocorrelation function of the residuals which was far from the correlation functions for white noise, which is the assumption of the technique.



After bringing in two additional terms, there was a dramatic improvement in the fit of the data and also in the shape of the autocorrelation function of the residuals. There is the fit to the measured time history based upon the estimated aerodynamic model. You can see the difference between the measured and computed data indicated by crosses.

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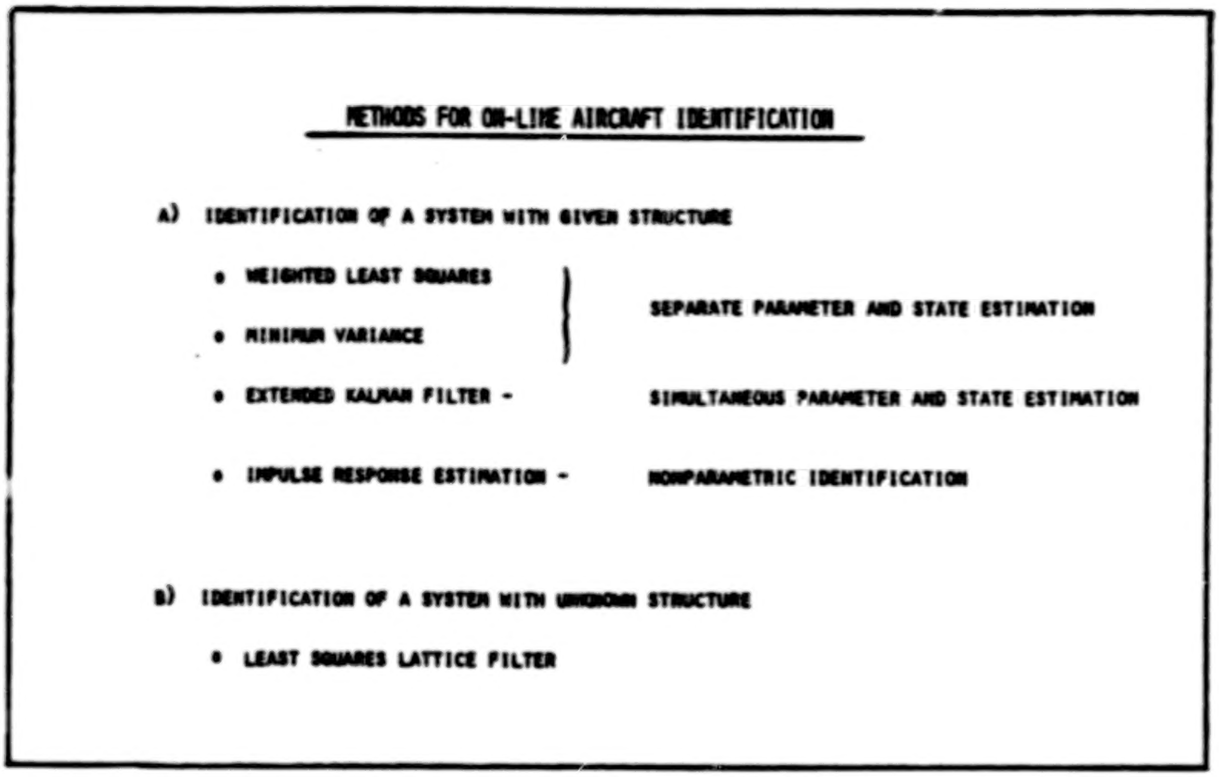

METHODS FOR ON-LINE AIRCRAFT IDENTIFICATION

A) IDENTIFICATION OF A SYSTEM WITH GIVEN STRUCTURE

- WEIGHTED LEAST SQUARES
- MINIMUM VARIANCE

} SEPARATE PARAMETER AND STATE ESTIMATION

- EXTENDED KALMAN FILTER - SIMULTANEOUS PARAMETER AND STATE ESTIMATION
- IMPULSE RESPONSE ESTIMATION - NONPARAMETRIC IDENTIFICATION

B) IDENTIFICATION OF A SYSTEM WITH UNKNOWN STRUCTURE

- LEAST SQUARES LATTICE FILTER

Now, let us go very briefly to the available methods for on-line aircraft identification. I would like to emphasize from the very beginning that the group I am working with has no experience with this type of technique. This summary is based more on reading and talking to people who are involved in this type of experience. It can be seen that the on-line methods for identification can be again divided into two groups. One is the method for the identification of a system with a given structure. The other is the identification of a system with unknown structure.

In the first case, there has been some attempt to develop the weighted least squares technique and the minimum variance technique which give you separate parameter and state estimations. We have already mentioned the extended Kalman filter. When these techniques were applied, ignoring their connection with the automatic system on board the aircraft, it was found that the minimum variance and the Kalman filter were better than the weighted least squares. But when these techniques were associated with the actual control system, the best performance was obtained from the simplest technique, which is the weighted least squares method. In all instances, only the simulation data was used. These two techniques give separate parameter and state estimations, whereas the extended Kalman filter gives simultaneous parameter and state estimations. The fourth technique was applied in France by researchers who designed a control system where the estimator estimates the impulse response rather than the parameters of the system. So we might talk about a technique for the nonparametric identification of a system. This technique was applied in a simulated experiment and not on-line.

Finally, there is a recent technique which could be used on-line and which has the capabilities at least to estimate, not only the parameters, but also the order of the system. This technique is based upon the so-called least squares lattice filter. It is the application of the least squares filter to the problem of on-line identification of a system with unknown structure.

SUMMARY

- OFF-LINE IDENTIFICATION WELL DEVELOPED AND IMPLEMENTED
- ON-LINE IDENTIFICATION TESTED IN SMALL NUMBER OF SIMULATED STUDIES

MAIN PROBLEMS OF ON-LINE IDENTIFICATION:

1) AIRPLANE PARAMETERS HAVE VARIOUS DEGREES OF SENSITIVITY AND VARIABILITY
2) AIRPLANE CAN CHANGE FLIGHT CONDITIONS WITHOUT SUFFICIENT RESPONSE EXCITATION
3) AIRPLANE WITH SAS HAS DEPENDENT CONTROL INPUTS

In conclusion, I would like to summarize my presentation by stating that the off-line identification is very well developed and implemented, whereas the on-line identification has been mostly tested in a small number of simulated studies only. The main problems we found with the on-line identification are the following. The airplane parameters, in general, have various degrees of sensitivity and variability, and this complicates the problem during the estimation off-line because it can result in the so-called identification problems for various parameters. The airplane can change flight conditions without sufficient response excitation. Therefore, in some instances, we cannot get the data used in the identification process, and there is not enough information for obtaining a reasonable estimate of the parameters. The third problem is that an airplane flying with a SAS system has dependent control inputs, which can again lead to identification problems.

SELF-REPAIRING DIGITAL FLIGHT CONTROL SYSTEM

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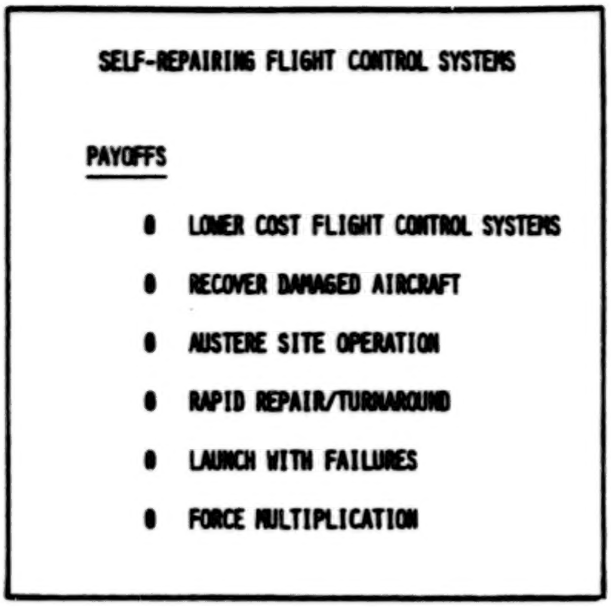


SELF-REPAIRING FLIGHT CONTROL SYSTEMS

PAYOFFS

- LOWER COST FLIGHT CONTROL SYSTEMS
- RECOVER DAMAGED AIRCRAFT
- AUSTERE SITE OPERATION
- RAPID REPAIR/TURNAROUND
- LAUNCH WITH FAILURES
- FORCE MULTIPLICATION

The first viewgraph indicates the various subject matters that we are trying to address. What I want to do is give you a little perspective of how we in the Air Force look at what you have been calling restructurable flight controls. We do have an ongoing program called self-repairing digital flight control systems. Some of the things I want to bring out are the general concept of self-repairing flight controls and what it means to the Air Force.

I am sure you have discussed many things already, but I will give you a little bit of the background of what has led up to where we are now. We started several years ago getting involved with analytic redundancy and this has got some studies into flight test. I know other people have been involved with it. NASA has the F-8 flying with analytic redundancy and other people have done studies in this area. But the results that we have been getting, at least on our DIGITAC A7 program, have been extremely encouraging to us in the sense of being able to identify and/or synthesize what we would normally sense with other sensors. And using that to compare with other signals, we are able to detect, if we only had two sensors, which one is good and which one is bad, and to continue to operate with another level of redundancy in there. This is very limited to what we have explored so far but it gives us a strong encouragement to proceed into something of a larger scale.

The next area that we have looked at has been the area of dispersed/reconfigurable flight controls. This is a study effort that was done for us by Grumman. It involved two elements: dispersal -- how far should we disperse the elements to survive small arms fire up to 37 millimeters; and reconfiguration in the face of loss of a control surface -- could we use alternate control surfaces to be able to recover the aircraft? And, just based upon the studies and simulations that were done in that program, it looked very encouraging.

As a matter of fact, one of the conclusions drawn was that reconfiguration of control surfaces offers the greatest potential for improvement of any flight control survivability.

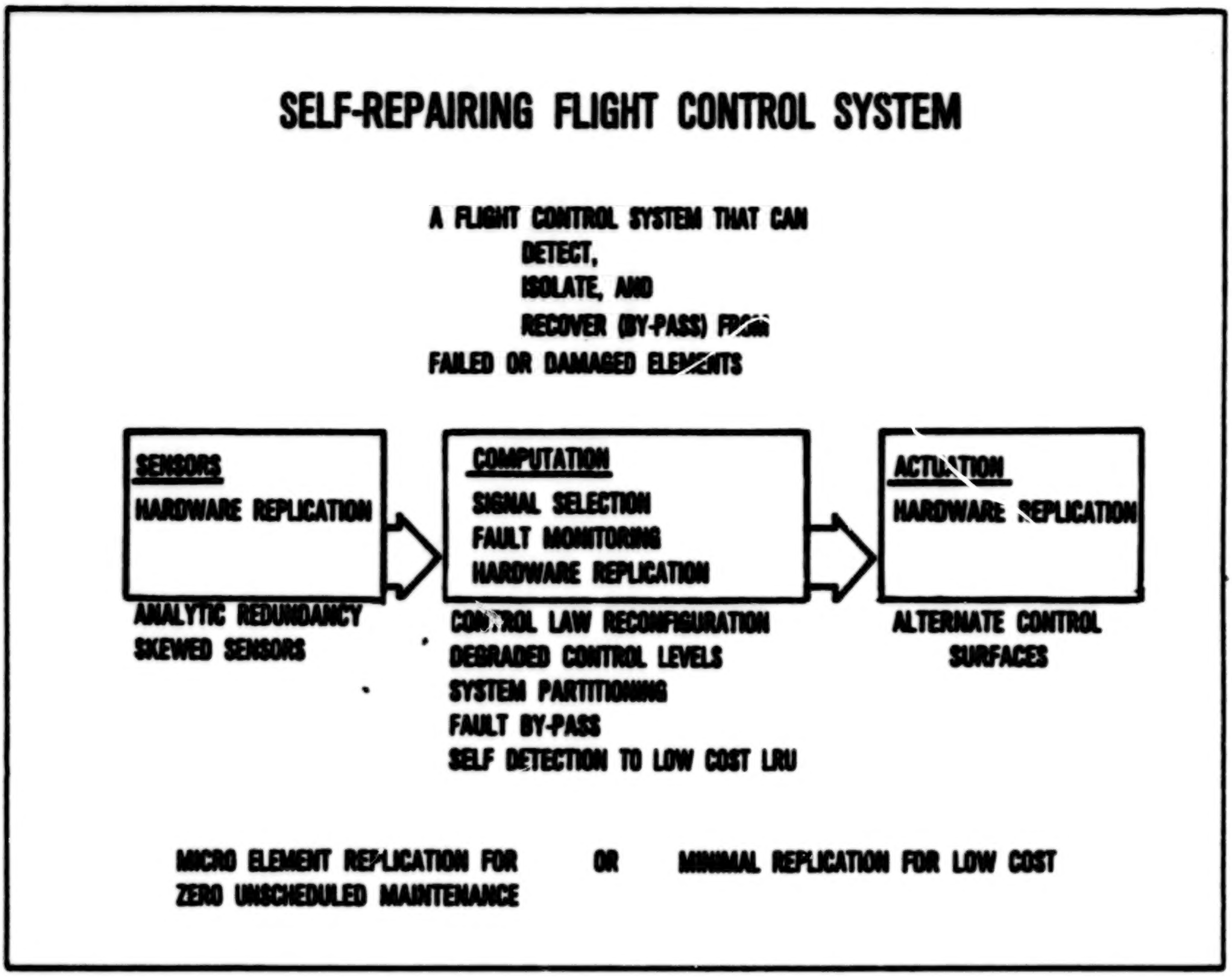
The next area that we have going on now is integrated inertial strapdown sensors or multifunction sensors, as some people like to call it. Work in this area started some time ago with studies and we are planning to get into flight tests later on this year. Basically, this is where you use common sensors for flight control, navigation, fire control, anything that requires inertial sensors using skewed sensors. I know the Navy has sponsored a lot of activity in this area. But the idea here is to try to pool the resources to obtain three-axes attitude, rate, and acceleration information and have a larger array of information available for all these elements that I mentioned: flight control, fire control, and navigation. The thing that we are now going into, and plan to flight test, is the normalization problem that you might have in terms of where you locate the sensors. Using two packages separated from each other, can we get the proper normalization of the sensors? The other element that we are looking at there is what effects structural modes might have because of the fact that they are located in different areas. Can we compensate for these? Can we handle the redundancy management of these sensors where we have multiple signals coming out of one package and combine them with something coming out of the others? This activity is projected to provide quite a payoff in terms of cost savings from going with this approach. Also the improvements in survivability look quite tremendous.

The next item that affects this overall activity is the work going on in microprocessors. The primary thrust here is to be able to do more processing at lower costs. And the concept of parallel processing comes into play, of being able to do things in parallel as opposed to everything being done in serial fashion which minicomputers have forced us to do. The work going on in that area is very encouraging and there is quite a bit of activity going on. And one of the things we want to do is put ourselves in a position to capture the technology coming out of the activities like the VHSIC program.

The next area that has an impact on the overall situation is what is going on in the areas of actuation. Traditionally, actuators, when we start interfacing them with fly-by-wire type flight control systems, have become quite complex, quite costly items that are prone to, at least when they use hydraulic amplification, problems of contamination and things of this type which cause undefined failures to occur. The basic power actuator is quite reliable and quite a good design. But there are things that we are looking at, such as direct drive valves, as we have been calling them and some people might call them other devices, to transfer from the hydromechanical type of complexity with which we have achieved the redundancy and the amplification of the signal into the electronic area. I believe we could be able to handle the electronic area with better finesse than what we have been able to do in the hydraulic actuator system. We have very precise hydraulic actuator designs, very fine designs from the standpoint that they might be considered engineering marvels, but they are extremely costly and expensive. Other activities going on in that area include work going on electromechanical actuation and I know that NASA Langley has been looking at the concept of an all electric airplane as well as us and the Navy. So there are other areas here that offer encouragement for improvements in this area of how we actually provide the muscle in the control system.

Another thing that we have been doing is sponsoring some thesis topics for Master students. We kind of capture these students for 6 to 9 months and give them a particular problem to work on and, by going through a series of these, we are able to get quite a free benefit for us. And some of the things we have been looking at are the robustness of new multivariable design techniques, like being able to handle situations such as a loss of a control surface or sensors, things of this type. We have gotten a little bit, not enough, into the aircraft modeling itself. What really happens when a surface is damaged, lost, or is no longer functioning? What happens to the aircraft model and all the various characteristics in the model itself?

The last item and the one that I will be talking more about is the self-repairing digital flight control system contract which started in 1980 and has been going on since. It is pretty well wrapped up now in terms of the technical effort but there are still a few items left.



SELF-REPAIRING FLIGHT CONTROL SYSTEM

A FLIGHT CONTROL SYSTEM THAT CAN
DETECT,
ISOLATE, AND
RECOVER (BY-PASS) FROM
FAILED OR DAMAGED ELEMENTS

SENSORS
HARDWARE REPLICATION

ANALYTIC REDUNDANCY
SKEWED SENSORS

COMPUTATION
SIGNAL SELECTION
FAULT MONITORING
HARDWARE REPLICATION

CONTROL LAW RECONFIGURATION
DEGRADED CONTROL LEVELS
SYSTEM PARTITIONING
FAULT BY-PASS
SELF DETECTION TO LOW COST LRU

ACTUATION
HARDWARE REPLICATION

ALTERNATE CONTROL
SURFACES

MICRO ELEMENT REPLICATION FOR
ZERO UNSCHEDULED MAINTENANCE

OR

MINIMAL REPLICATION FOR LOW COST

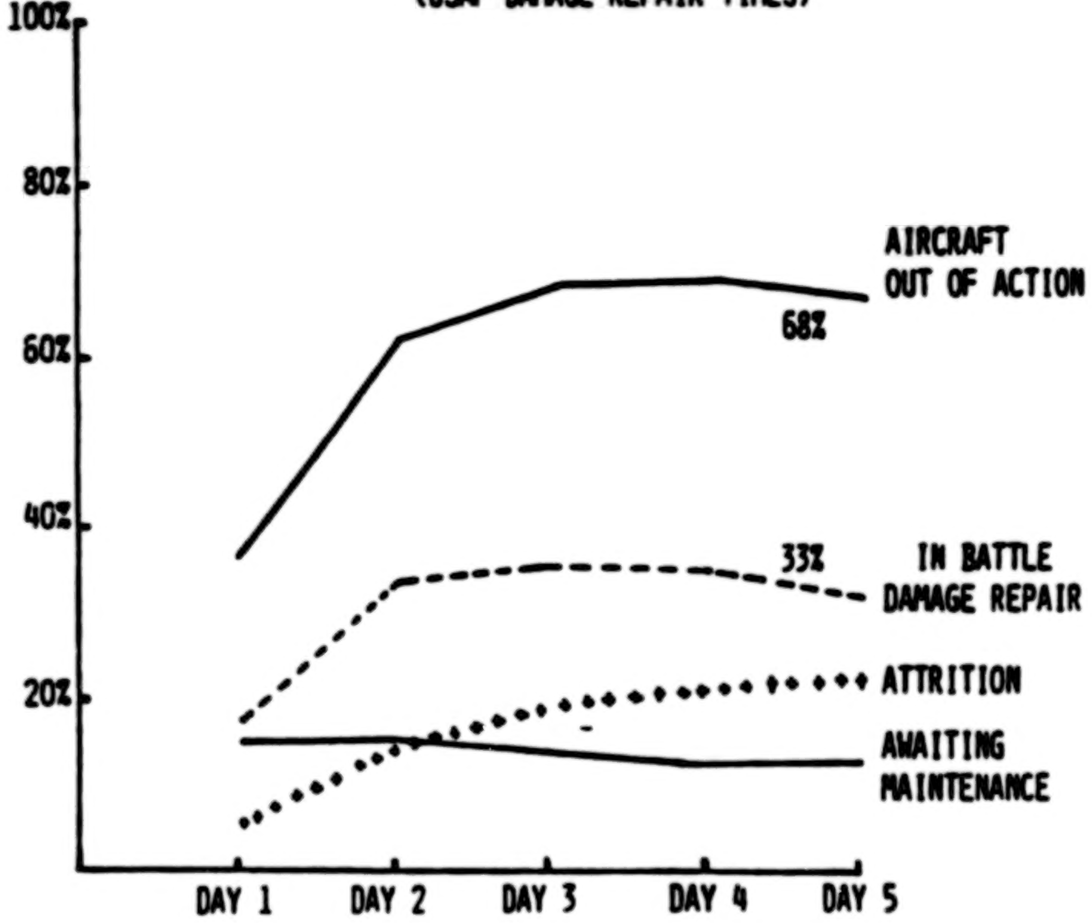
The basic concept probably is best described by going on to the next viewgraph. What we had laid out when we started this program is to primarily use the items that are healthy in the control system as much as we can instead of concentrating on rejecting faults or eliminating the bad items in a mass of replication of hardware to get around the faults. The idea is to try to find better and more novel ways to use the healthy items.

Indicated on this chart, primarily in the enclosed areas, are the traditional ways in which flight controls have been dealt with to provide the reliability and the fault tolerance. The set notes that hardware replication or redundancy is the primary approach that is being used. The things down there in the open area in the chart are areas that have been looked at in the past, probably separately, maybe in some combinations. But what we wanted to do in this program was to take a system look--to put all these things together as much as possible, to see how these things could be pulled together, and to determine what kind of benefits we could be achieving if we did this. It was kind of a throw out the old ways, or not be tied to the old ways of doing things and try to come up with something new and novel. We thought at that time that there are probably two areas of payoff indicated on the bottom there. One is, we could use a large replication of microelements, microcomputers and things of that type to give us a concept of zero unscheduled maintenance where you would allow faults to accumulate and not do anything about them until the time that you schedule the maintenance action and you take care of them all. The system would have sufficient capability built into it to overcome any particular problem. Or an alternate way of looking at it would be to come up with some kind of minimal replication. One of the things that concerned us was the cost of airplanes and we needed to find some way of getting a very low cost airplane, just to match the numbers game that we are faced with in a lot of situations. Thus, being outnumbered, we need to find ways to get increased numbers and one way of doing this is to drive the cost of the basic unit down, and so that was another kind of basic goal that was coming out of this.

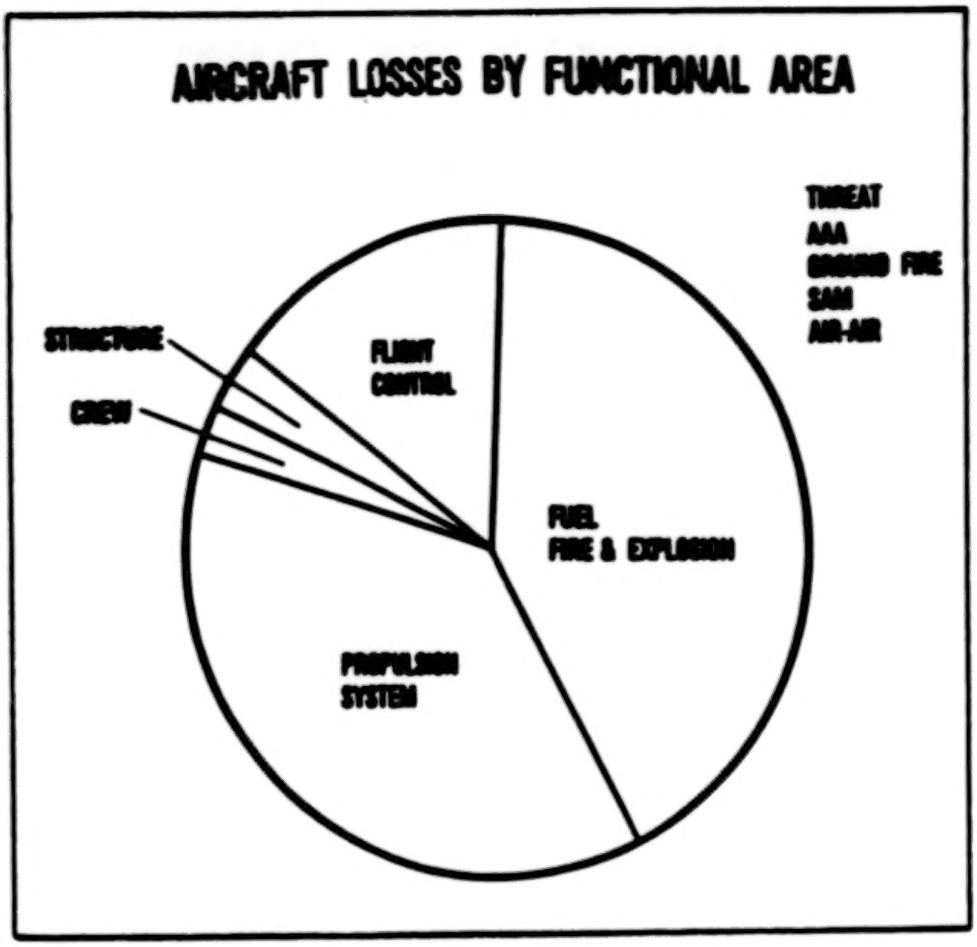
SOME ABDR INSIGHTS BASED ON COMBAT DATA

Then as we got into the program there were some other areas investigated as we can see on to the next viewgraph. Aircraft battle damage repair (ABDR) was gaining a lot of emphasis in the Air Force. And I just want to give you some insight as to what is going on here. It is not only Air Force wide, it is now under the auspices of the Joint Coordinating Group for Aircraft Survivability. They are looking at what can be done to give us, not only rapid repair, but the technology to give us hard, new techniques that would give us tolerance to damage as well as rapid repair of damage. One of the things that we found was that there was very little work in that type of program, and very little overall activity that involved flight controls. And that was of some concern to us. We talked to the people about this and got more involved with this activity.

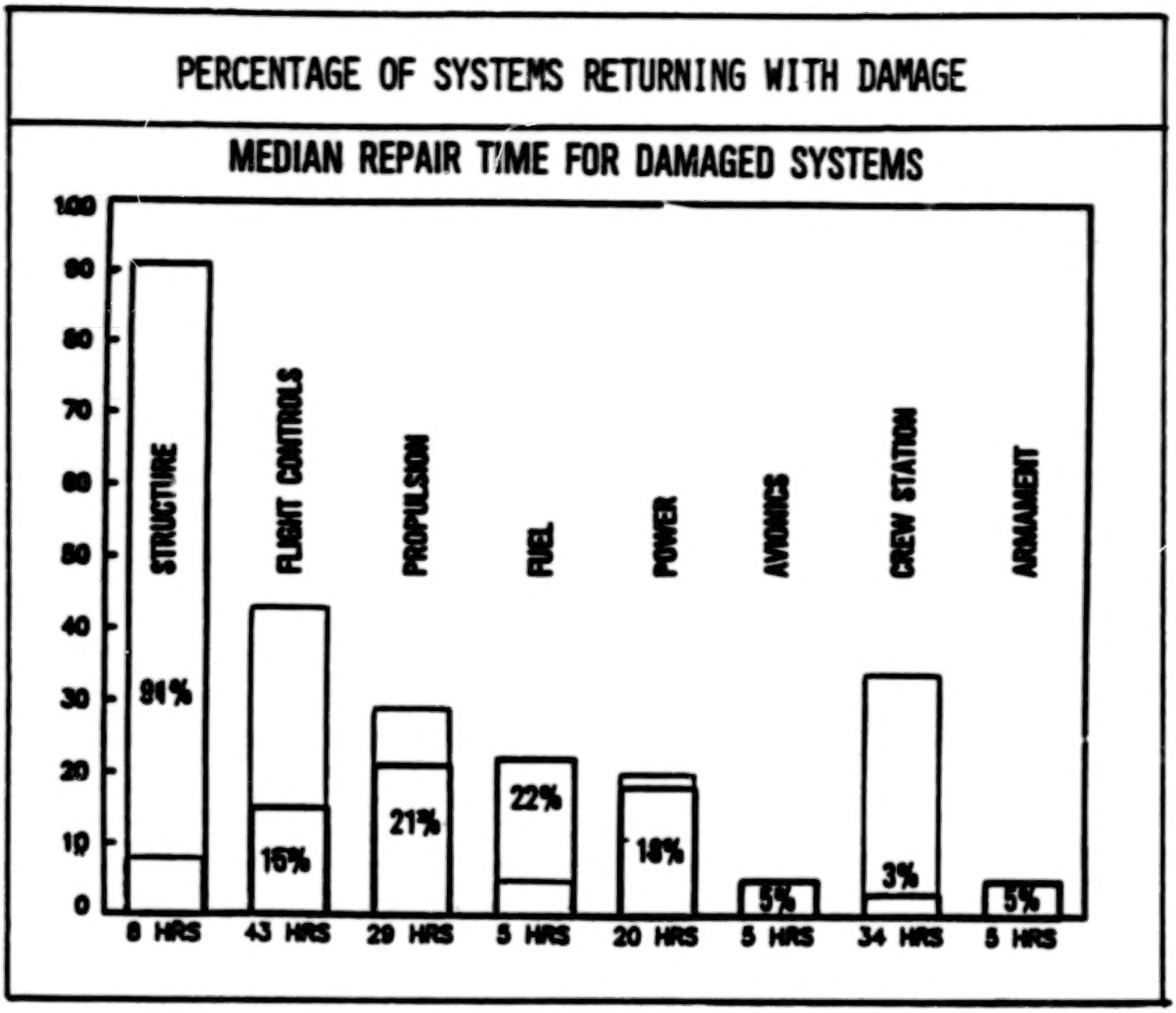
FIGURE 1: STATUS OF FLEET DURING SURGE
(2.88% ATTRITION)
(4 TO 1 DAMAGE/LOSS RATIO)
(USAF DAMAGE REPAIR TIMES)



Going on to the next viewgraph, I will give you a little bit of insight into what the situation is. The graph shows the status of the fleet during a very intense combat scenario. During a surge, by day 2 it is projected that over 60 percent of the aircraft would be out of action. This is due to the areas listed below--attrition, awaiting maintenance, or battle damage repair. And the basic thought here is that you are down to less than half your fleet by the second day. And it does not get any better after that. So there has to be some way of turning this around. Again, it is a basic problem in just meeting the threat that is out there.



So, the next viewgraph is kind of an indication, based upon some examination that was done, of the areas that have been contributing to the loss of an aircraft during combat situations. And flight controls account for about roughly 20 percent of the losses based on that analysis that was done. But there is another negative statistic that really is hard to quantify in any sense and that is the number of aircraft that return and where the damage occurs. And they have plotted graphs, and I do not have a graph for it, but they have plotted where the holes in the airplane were as they returned from combat situations, primarily in Southeast Asia. If you look at these you notice that in the critical areas, where the control surfaces and the actuators are, there is quite an absence of holes or hits in those areas. The supposition is, I guess, or it suggests to us anyway, that if the aircraft were hit in those areas, that the aircraft did not return. So it is, as I said, not a quantifiable situation, but we feel that something has to be done to protect the aircraft and to recover those aircraft so we get more back.


PERCENTAGE OF SYSTEMS RETURNING WITH DAMAGE

MEDIAN REPAIR TIME FOR DAMAGED SYSTEMS

Going on to the next viewgraph, there is another element associated with battle damage repair that has to do with how many of the various systems within the returning aircraft are damaged. Of those that have damage, some of them only have damage in one area, some have multiple damages, and so forth. But this chart is a representative plot of the situation. I forget the number of situations and the number of aircraft that we looked at. Structures are the surrounding things and you know that they are going to get hit just about any time that any subsystem is. So that is the reason why it has such a high percentage, 91 percent. Flight controls is only shown to be 15 percent in this particular chart, but if you take a look at what this means as far as getting that aircraft turned around and back into flying status, now we are up to over 40 hours, actually 43 hours on the median time to repair a flight control system. And it is the highest one shown there. So even though the number of times that a flight control element is damaged is low, the time it takes to repair it to get it back into service is quite high. And it becomes one of the primary drivers. If the structure is the primary driver, in terms of number of times, or total hours that are required to repair, the flight controls equal pretty much what is required for the structure. Now, if you get into more massive damage by larger elements, missiles, etc., the situation changes a little bit. The flight controls are still quite high. The propulsion goes way up primarily because of the damage of the various elements in the control system, the structure, and the surrounding things take quite a while to repair.

AIRCRAFT BATTLE DAMAGE REPAIR

TECHNICAL ISSUES

- ABDR DATA/TECHNOLOGY OPPORTUNITIES
- DEFERRABILITY/REPAIRABILITY
- ABDR ASSESSMENT TECHNIQUES
- ABDR RESOURCE QUANTIFICATION
- ABDR CRITERIA & DESIGN

PAYOFF

- INCREASE COMBAT SORTIE GENERATION BY 35%

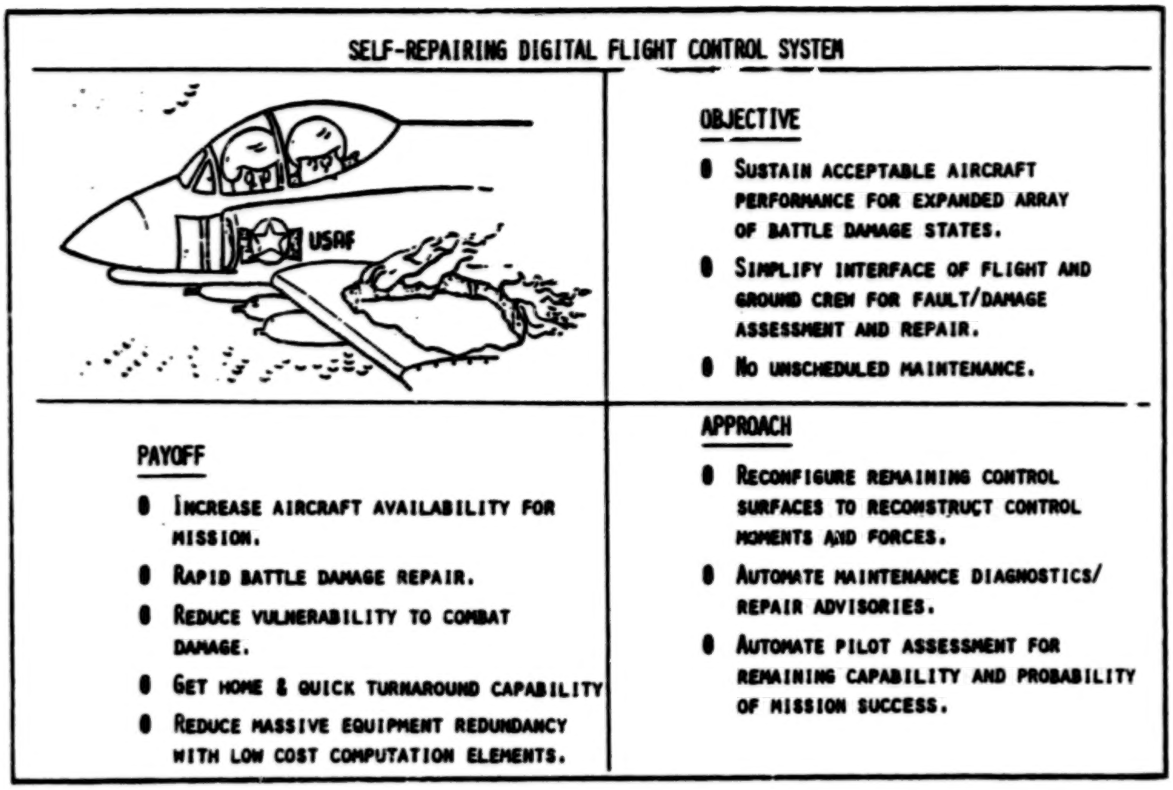
So as far as the aircraft battle damage repair ideas are concerned, they have listed issues, separate from us, that they want to address. They want to look at all the technical opportunities available here.

The first choice of what they want to build in the future is to defer repairability. Defer the need to repair items. In other words, if you can fly with minor damage, etc., go ahead and do so and defer repair until a more convenient time, if that ever occurs. And if repair is necessary, then do it very rapidly so you can get the aircraft flying. The primary thrust of all of this is to achieve the required number of sorties that they are going to have to meet, the multiple missions per day, etc.

The need is to have rapid assessment techniques of what can be repaired and what has to be put off, so they can concentrate on those things that can be repaired in short time. You have to remember the austere conditions that these crews will be operating in; they might have hostile elements involved in terms of enemy threats, in terms of chemical and biological warfare and the types of suits they have to work in. So there are a lot of situations that these crews are training themselves to work in. We need a set of criteria on how to handle some of these problems. It kind of scares me looking at some of the things that they are trying to do. Right now, for mechanical linkages, they are putting a wooden dowel, or whatever might be available in there, as a temporary fix and putting bolts through each side to repair damaged pushrods, for example. There is quite a problem with wires and wire bundles in that not only do the wires get shattered, damaged, etc., but because of the situation that they sometimes tend to fuse back together. So the massive wire bundles is also a problem.

The tools that they have to work with are somewhat limited. They do not have all the extensive amount of tools available. So, it is quite a set of austere conditions under which the aircraft are going to have to be repaired in battle. And they are looking at ways in criteria and design, etc., of how to do this.

And the bottom line is, as I have said, to get more airplanes out there to meet the threat that is coming. They have to be able to survive and counteract the short war situation.



SELF-REPAIRING DIGITAL FLIGHT CONTROL SYSTEM

OBJECTIVE

- SUSTAIN ACCEPTABLE AIRCRAFT PERFORMANCE FOR EXPANDED ARRAY OF BATTLE DAMAGE STATES.
- SIMPLIFY INTERFACE OF FLIGHT AND GROUND CREW FOR FAULT/DAMAGE ASSESSMENT AND REPAIR.
- NO UNSCHEDULED MAINTENANCE.

PAYOFF

- INCREASE AIRCRAFT AVAILABILITY FOR MISSION.
- RAPID BATTLE DAMAGE REPAIR.
- REDUCE VULNERABILITY TO COMBAT DAMAGE.
- GET HOME & QUICK TURNAROUND CAPABILITY
- REDUCE MASSIVE EQUIPMENT REDUNDANCY WITH LOW COST COMPUTATION ELEMENTS.

APPROACH

- RECONFIGURE REMAINING CONTROL SURFACES TO RECONSTRUCT CONTROL MOMENTS AND FORCES.
- AUTOMATE MAINTENANCE DIAGNOSTICS/ REPAIR ADVISORIES.
- AUTOMATE PILOT ASSESSMENT FOR REMAINING CAPABILITY AND PROBABILITY OF MISSION SUCCESS.

Going on to this next viewgraph, I am really getting into the self-repairing concept. I have tried to give you a little bit of the background of some of the things that have gone on here. And try to get a little bit into the self-repairing activity and what is going on in this program. And as I have indicated, we want to really sustain an acceptable aircraft performance or provide acceptable flying qualities for much larger array of battle-damaged states. Self repairing could also apply to any other traumatic condition that might occur. I would like to use an analogy of the control system to the human neuromuscular system in terms of the way it functions with the sensors and the means of transmitting information--the brain doing the computation and the muscles being the actuators, etc. The human body is able, a lot of times, to cope with traumatic conditions and to retrain itself to do certain things. It takes a period of time to do this, and that is the kind of thing that I would like to think that we are trying to train into flight control systems. We want them to be able to handle, in a very short time, these traumatic conditions and still satisfy safety of flight conditions. At the same time we would also like to improve the interface with both the flight crew and the ground crew in terms of giving them positive assessment or positive alert of what is happening as opposed to negative type of alerts, and to provide automatic means by which they can assess what the damage is and what they have to do to repair it. And then the other element, in so far as the objective, is to strive for zero unscheduled maintenance, if we can.

Listed here are the approaches that we are using. The basic thing is to be able to have sufficient smarts in the controls system so we can identify when something has gone wrong or when a control surface is damaged and then be able to reassign or reallocate the authority to reconstruct the forces and moments on the aircraft to other control surfaces, at least to a sufficient extent. You may have an aircraft that, instead of being a 9g airplane, might be a 3g airplane or something of that type, but the basic thrust is to be able to reconstruct sufficient moment and forces to control the airplane. We also want to do a lot of automation of the maintenance diagnostics, repair advisories, and provide a capability to the pilot so that he knows not only that something has gone wrong, but it tells him more about what has happened, what he might have to do, and also what his probabilities might be, not only to recover the aircraft, but to continue the mission. I think that we are moving into that stage. It might involve a lot of other subsystems in terms of gathering sufficient information to get into this probability of mission success, but I think that it has to start some place and that the thrust can be driven in that area to achieve this capability.

Listed there in the lower left are the kinds of payoffs that we see coming out of this. Probably the first thing that we want to do is to be able to recover an aircraft that otherwise might be lost. And then, if we can do that satisfactorily, we want to consider the possibility of being able to continue the mission and maybe go to a secondary target or do something that might be less demanding. Whether the pilot is mentally trained to accept those kinds of conditions and do that kind of thing is another situation that has to be addressed, but we want to at least provide that type of capability for the control system. I think that we are going to gain quite a force multiplication in terms of being able to use aircraft more frequently; and once the aircraft is launched and committed to a mission, we will be able to continue the mission and get something accomplished without having to recover and essentially lose that whole flight, the time, and everything else. Several aircraft may turn the tides of the battle in this particular case. I think also that the bottom line is that, if we can rely on low cost elements, we can get a reduction in the overall redundancy level. I will get more into what I mean by this a little bit later.

SELF-REPAIRING DFCS

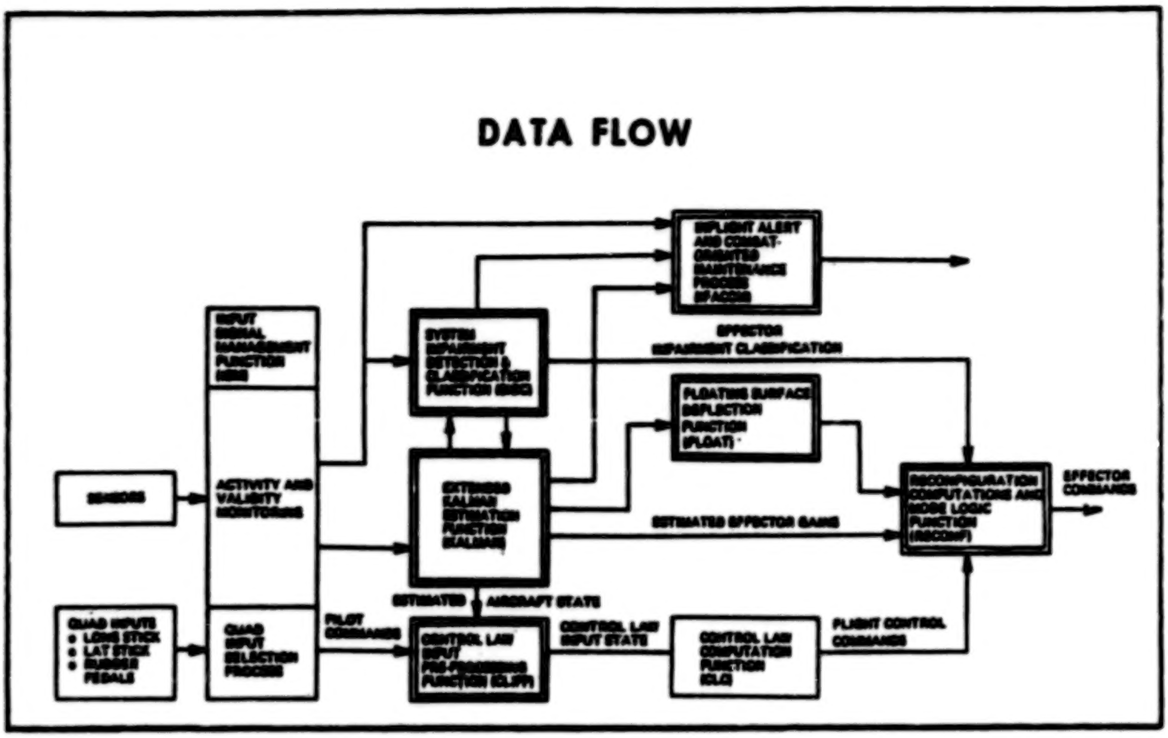
CONCEPTS

- **RECONFIGURATION**
- **INFLIGHT ALERT**
- **COMBAT ORIENTED MAINTENANCE DIAGNOSTICS**
- **COST EFFECTIVENESS PHILOSOPHY**

Going on to the next viewgraph, the various elements, or concepts that we have now in the self-repairing control systems are these four that are listed there. Three of them are technical and the other one is a cost item. The first concept is reconfiguration to continue the mission if possible; and if not possible, then to recover the aircraft when something is damaged, and to use the healthy elements to the maximum extent possible. We are also thinking of using reconfiguration as a level of redundancy, maybe to replace other levels of equipment redundancy that we have. For example, we would use that reconfiguration structure in the same way as we would use the last two channels of a conventional flight control system that we have. By reconfiguring, we are able to provide the same level of reliability or the same level of survivability that we would possibly provide with a totally quad system, for example.

Inflight alert, as I mentioned, is kind of a negative alert. A light comes on and tells the pilot that something has happened. But, what does he do about it? What does this really mean? And while he thinks about it something is happening. What we need is something that is more positive. Two things are necessary to automatically take care of the situation for the pilot. Attempt to keep him positively alerted as to the situation. But what does this mean to him? What does it mean as far as what he is going to have to do in the immediate future to cope with the situation? The control system is now taking care of things for him but this is going to mean that certain other things are going to have to happen in the future. As far as what we call combat-oriented maintenance diagnostics, we are getting into the automation of a lot of things that are now in the Technical Orders (TO's). One of the basic problems we have found with a lot of aircraft is the skill levels that the people assigned to them have and the turnover of people in the maintenance areas. There is a lot of time spent going and looking up things in the TO as to what should be done, what does it mean, and what is the next step that they do. And when they trace down, sometimes they even run into dead ends on the TO's. As a result they really do not know what to do next. They may go and ask somebody else (about the problem) and learn that "Oh, I changed the actuator here and that solved the problem that I had." Such an answer may be totally unrelated but it sounds similar to their problems and so they go ahead and do something similar. We have a lot of equipment that is floating around back and forth in the supply system for which there are no failures identified and we cannot duplicate them. This is a costly process in itself. So we want to automate a lot of the things that are now in the TO's so that all the ground crew has to do is really access the control system and it simply tells or gives a good indication of what has to be done. Probably another element of that is to isolate down to a line replaceable unit so that, it can be replaced and very little repair, if any, will be done at the flight line unless it is damaged where they have to splice wires or things of this type. And I think a big payoff here, with respect to the wire bundles, is multiplexing--what it can do and what its impact is. Instead of running massive bundles of wires around the airplane, use a small bundle of wires that would be much simpler to maintain and to take care of in situations such as combat damage. Of course, there is a maintenance philosophy that operational organizations would like, and luckily we are driving toward it, and that is to have two levels of maintenance. One is the depot level and the other is the flight line level thus eliminating the field shop type of activity. So I think that this automation is driving us into that area also.

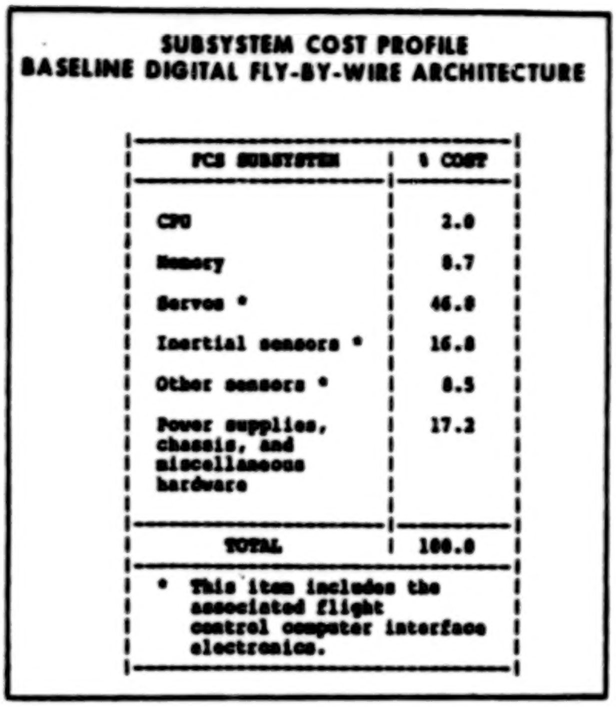
As far as the cost effectiveness philosophy here, I mentioned about using reconfiguration to pretty much take over one of the levels of redundancy. And, if we can do this intelligently, and rely on the cost advantage of the lost cost items, I think that we now can drive the costs down. I will get into this in a minute. But, it is not only the acquisition costs, but the operation and support incurred by the operational units that are big factors in terms of how and what the costs are for these flight control systems and the various elements in them.


DATA FLOW

SENSORS
QUAD INPUTS
• LONG STICK
• LAT STICK
• RUDDER PEDALS
INPUT SIGNAL MANAGEMENT FUNCTION (ISM)
ACTIVITY AND VALIDITY MONITORING
QUAD INPUT SELECTION PROCESS
PILOT COMMANDS
SYSTEM IMPAIRMENT DETECTION & CLASSIFICATION FUNCTION (SIDC)
EXTENDED KALMAN ESTIMATION FUNCTION (KALMAN)
ESTIMATED AIRCRAFT STATE
CONTROL LAW INPUT PRE-PROCESSING FUNCTION (CLIP)
CONTROL LAW INPUT STATE
CONTROL LAW COMPUTATION FUNCTION (CLC)
FLIGHT CONTROL COMMANDS
INFLIGHT ALERT AND COMBAT-ORIENTED MAINTENANCE PROCESS (IFACOM)
EFFECTOR IMPAIRMENT CLASSIFICATION
FLOATING SURFACE DEFLECTION FUNCTION (FLOAT)
ESTIMATED EFFECTOR GAINS
RECONFIGURATION COMPUTATIONS AND MODE LOGIC FUNCTION (RECONF)
EFFECTOR COMMANDS

Going on to the next viewgraph I will show you a little bit about the data flow that we have in the control system. The double-boxed areas are the areas that are new. Basically, if you look at it, the information flows from left to right as it normally does in block diagrams. You start out with the sensors or input signals--the transducers coming from the flight deck and so forth; and going to the bottom line, you end up with outputs to the actuator, if nothing is wrong. That is pretty much the same type of thing that we have had before. The control laws are processed much the same way going to each surface to do their job as required. We are also looking at things like extended Kalman filters and other items to identify and detect system impairments, to be able to classify what these are, and to feed them to various elements within the control system, so that we can determine what is wrong, what has happened, and know what to do about it. Some of the things that we are looking at include, not only the control surface reconfiguration, but what happens up in the sensor area also. We would like to be able to use more of the information that is on board the aircraft, but probably reduce the number of sensors that are required and dedicated to the flight control system, if we can, and share more information. So we are looking at all three basic elements: the sensors, the processing requirements, and the reconfiguration of the control surface and the actuation type devices that are required here.

Now let us concentrate a little bit again on the reconfiguration. Some situations may occur in which the actuator may be locked, or in other words, the actuator quit functioning; it may be damaged, or failed in itself, so the control surface, in that situation, can either be locked and centered or the surface may be floating. There may be complete separation of the actuator from the surface and so the surface winds up floating. Or it may be that the bearing point or something providing that surface rotation is jammed, or broken, and the surface is floating. Other things that can happen are that, due to combat damage or some other damage--it does not matter, part of the surface might be missing, or the whole thing might be missing, or part of the wing or something else might be damaged. So we are losing the effectiveness of the surface and it affects both the controllability and the stability. And it affects them differently in each situation that happens. Thus the idea of some of these elements, such as the Kalman filter and the impairment detection, is to be able to identify what the situation is and to supplement some particular gains or functions in an area here that we call floating surface deflection. Bring in something additional to take care of what has happened and to reassign this reconfiguration process to other surfaces. Whether it be flaps, spoilers, active flaperons, canards, whatever it is, we need a combination of surfaces to give us the moments and forces that we need on the airplane--to reconstruct them. The top block is the automation of the knowledge base required to give the crew (the flight crew and the ground crew) additional information. That is kind of the basic way that the system flows together. Some of the problems that I will get into later are: can we do all this identification and reconfiguration in real time, can we handle the processing load that is required, and what does this all mean.



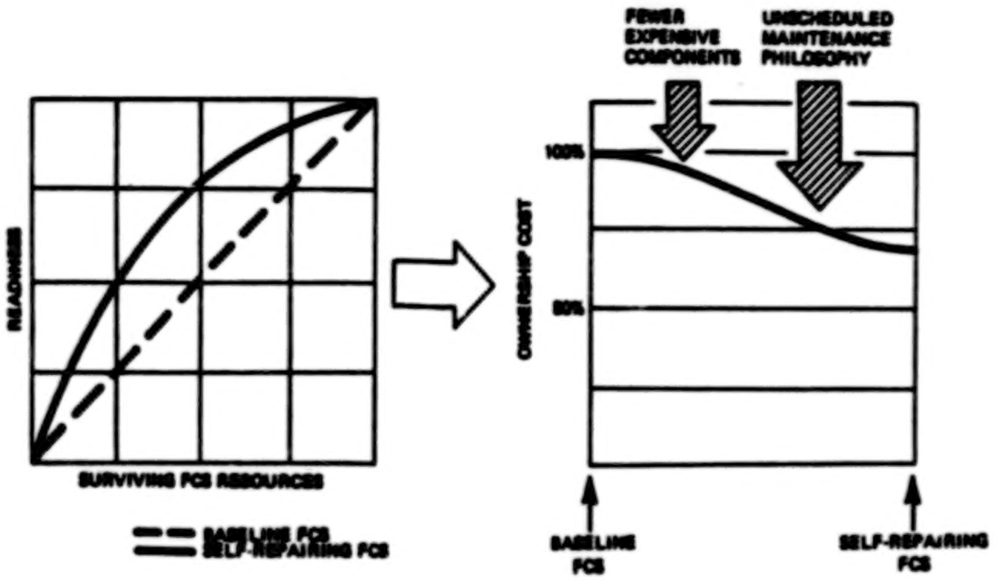
SUBSYSTEM COST PROFILE
BASELINE DIGITAL FLY-BY-WIRE ARCHITECTURE

FCS SUBSYSTEM	% COST
CPU	2.0
Memory	8.7
Servos *	46.8
Inertial sensors *	16.8
Other sensors *	8.5
Power supplies, chassis, and miscellaneous hardware	17.2
TOTAL	100.0

* This item includes the associated flight control computer interface electronics.

The next viewgraph shows a subsystem cost profile as a percentage of cost of the total flight control system, excluding the power actuators. This shows how the system cost breaks down. It is quite surprising that, even today, digital systems including a lot of the software development costs amortized over the total system buy. It comes out to where the CPU and memory are roughly on the order of 10 to 12 percent. If these numbers were reexamined they would probably have to be adjusted a little bit. But still, even using today's minicomputers, this shows that the cost of the digital elements are very low. And if you look where the big cost drivers are, it is in the servo actuators, which includes electronics for these, and in the inertial sensors as well as the power supplies, etc. But I think that, if we concentrate on driving the costs down on the big drivers and accept a cost increase in the areas where we are already low in cost--and the new technology in microprocessors is driving the costs down, we could get an overall cost reduction in the whole flight control system if we can make inroads into these big areas. And so to me this is quite an eye opener considering that there is a tremendous amount of work going on in terms of developing microprocessor-type architectures and a lot of technology in this area where the cost is only 10 percent of the flight control system cost. Where we really could make big gains is if we drive the costs down in these other areas. And if we keep a system approach, we can probably do a lot more than if we just try to come up with lower cost elements there.

REDUCED PEACETIME OWNERSHIP COSTS



What this all means, in terms of peace time operation as well as the readiness of the aircraft for battle conditions or any other conditions, is that we think we can get an increase in readiness of the aircraft by looking at things like self-repairing concepts and the various concepts that we have. How much increase can be achieved really has not been quantified yet, but the trend looks very promising in terms of getting a tremendous increase in readiness when reduced levels of resources available to the flight control system result, either due to internal failures or damage from external situations. And the overall cost picture, in terms of how we can reduce the level of redundancies in some areas, leads us to develop more smarts into the aircraft and the control system, to drive ourselves into the new maintenance philosophies that the Air Force is looking at, to reduce or eliminate the field level of maintenance, and to get more into the unscheduled maintenance philosophy. They have come up with a goal of an overall reduction of the flight control system of 30 percent, just for operating it in peace time. Normally, the situation is such that we would like tremendous amounts of flexibility and capability in there for survivability reasons to have that aircraft available to do the job it is intended to do. And this has driven us into an extremely high cost for operating aircraft; but we usually operate them, thank God, in peace time situations. So, I think we can get the best of both worlds by looking more at a system approach and what some of the new technologies can do for us.

SELF-REPAIRING FLIGHT CONTROL SYSTEM

TECHNICAL ISSUES

- FAULT/DAMAGE IMPAIRMENT PROCESS
- RECONSTRUCTION OF CONTROL MOMENTS/FORCES
- IMPAIRED AIRCRAFT MODEL
- SYSTEM ARCHITECTURE/PROCESSING REQUIREMENTS
- CREW INTERFACE MODULES
- SYSTEM READINESS ASSESSMENTS
- SYSTEM DEMONSTRATION

The next viewgraph addresses some of the technical issues involved here. I think these are some of the major areas of work that really need to be done. We have laid out the basic concepts for this, taking a look at some of those things that I think we can do. We have done the reconfiguration in non-real time simulations but the fault/damage impairment process, combined with the reconstruction of the control moments and forces, has to be demonstrated to show that it can operate in real time and that we are not driving ourselves into unacceptable burdens in terms of computation capability. And I think that these are some of the technical issues that have to be addressed, worked on, and demonstrated. It must be shown that these concepts can work before any of these ideas are going to be accepted in a total aircraft system sense.

Another area that I am concerned about is the models that we use for the aircraft in the impaired state. What is the total effect on all these cross-coupling terms, that we have driven pretty much to zero or into second and third order effects, when we have impairments in the control surfaces? Are these now going to become predominant? I do not think that we have really looked at it. Neither the models nor the wind tunnel situation really shows us what really exists out there as far as what the aircraft characteristics are. And I think we really need to build up a better understanding of what has happened to the aircraft under these impaired conditions. What you try to simulate and duplicate on a simulator, for example, may not be what actually existed in that aircraft. I was reading over again the two situations attached to the workshop invitations and the idea that a simulator test shows what could have been done by putting the pilot, without knowing what is going to happen, into that situation. I think there is another condition that probably was not looked at, and that is, the extent of the effect of the damage on the total aircraft stability and control characteristics. What you may have looked at on the simulator may not have really truly represented the actual situation. I believe there is a lot of work that has to be done to improve some of these things. We are trying to look at the use of some prediction techniques to try to generate some of these things. But I would really like to have a better feeling that the models we are using are the correct ones.

For the system architecture and processing requirements, once we have identified what the algorithms are to do the fault/damage impairment process, the reconstruction, etc., then we have to put it together and really look at the processing requirements. How are we going to handle this, do it effectively, do it safely, and satisfy all of our reliability and safety requirements?

We have to involve human interaction in terms of the crew interface modules. But, what really makes sense, is to show the pilots and the ground crew what really has happened and what to do about it. Can we automate this procedure? What should we really tell them? There are some feelings that, as far as the pilot is concerned, you just automate everything and you do not tell them that anything is wrong. He will sense that something is wrong and his first inclination will probably be to go home. But I feel strongly that, if we could give them the right intelligent information and the proper training, eventually they will learn to accept that these traumatic conditions occur and that they may be able to accomplish something else while they are there. He has already got his life in jeopardy, as far as being an Air Force pilot, so maybe he can go out and accomplish a secondary mission.

As far as system readiness assessments are concerned, I think we just need to do much better than what we have done in the past. We need to really automate these so that we can tell very rapidly exactly what has to be done and what areas have to be worked on. We do not want to require a lot of repeated tests and judgement on the part of the ground crew. There is still a certain amount of systems analysis and assessment work to be accomplished that addresses the total system. We have looked at the individual elements and tried to generalize from these to obtain projections on the aircraft readiness, but all the interface and coupling areas have to be addressed as well. We need to quantify the actual improvements in readiness through the application of self-repairing concepts.

Once the elements have been developed to include coding and implementation in real-time processing, all the elements have to be operated as a system. We need to demonstrate that reconfiguration can be done in real time without severe transients. We also need to demonstrate that maintenance technicians can readily assess and diagnose the flight control system fault and damage using the self-repairing techniques.

SELF-REPAIRING FLIGHT CONTROL SYSTEMS

PAYOFFS

- LOWER COST FLIGHT CONTROL SYSTEMS
- RECOVER DAMAGED AIRCRAFT
- AUSTERE SITE OPERATION
- RAPID REPAIR/TURNAROUND
- LAUNCH WITH FAILURES
- FORCE MULTIPLICATION

Using self-repairing concepts, in particular the reconfiguration element, eliminates a layering of redundancy. Even though the cost of digital logic increases, the overall flight control system cost is reduced. Reconfiguration will permit recovery of some aircraft heretofore lost due to traumatic conditions such as battle damage or massive changes in the flying characteristics. Automatic maintenance diagnostics self-contained in the aircraft will allow operation from austere sites where sophisticated ground support equipment is not available. These diagnostics will assist in turning the aircraft around in much shorter time, and getting it back into combat.

Self-repairing systems could lead to an appropriate new policy of being able to launch with failures instead of having to have everything full up and operating before you launch the aircraft. If the failure is in an area that we still have sufficient resources to cover, then we go ahead and launch the aircraft. And through all of that we will get a force multiplication for the Air Force particular needs.

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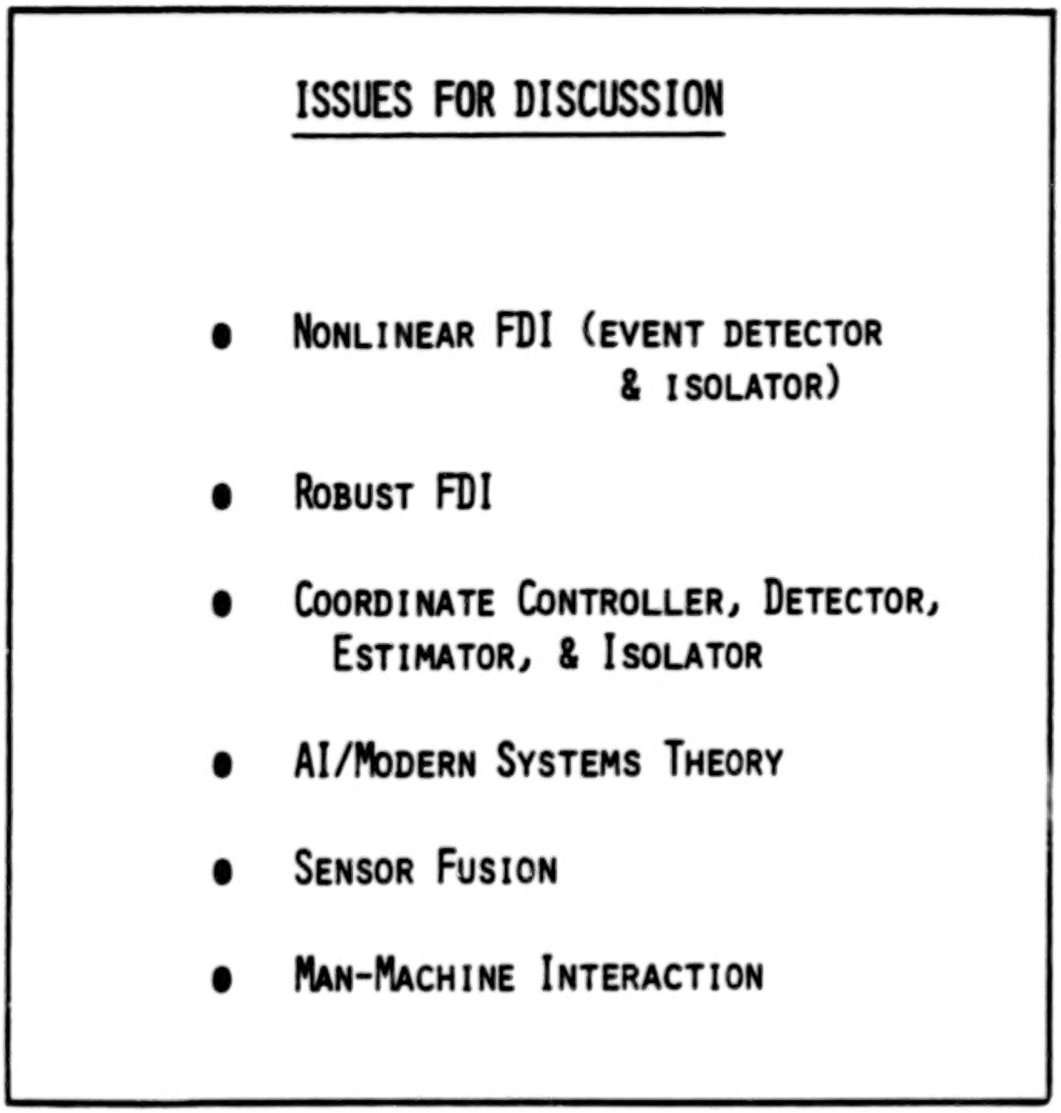
STATE-OF-THE-ART THEORY APPLICATION

Sol Gully
ALPHATECH
Burlington, MA 01803



ISSUES FOR DISCUSSION

- NONLINEAR FDI (EVENT DETECTOR & ISOLATOR)
- ROBUST FDI
- COORDINATE CONTROLLER, DETECTOR, ESTIMATOR, & ISOLATOR
- AI/MODERN SYSTEMS THEORY
- SENSOR FUSION
- MAN-MACHINE INTERACTION

This is not intended to be an all encompassing presentation. These are just a few comments that were either missed or could be the subject of further discussion among the people at this workshop. I have listed several issues for discussion in this viewgraph.

NONLINEAR FDI

(EVENT DETECTOR & ISOLATOR)

- CAN CHARACTERIZE ANY DETECTABLE EVENT
  - MAY MAKE PROBLEM NONLINEAR DEPENDING ON HOW THEY ENTER SYSTEM (E.G., GEOMETRY)
- SOLUTIONS: PREFILTER, LINEARIZE, DIRECT SOLUTION
  - SIX DEGREES OF FREEDOM APPLIED TO TARGET MANEUVER PROBLEM. HERE WE MUST ESTIMATE DIRECTION, MAGNITUDE, TIME, AND TYPE OF MANEUVER

The first issue is that we have all talked about the controls and how to linearize them and how to work with gain schedules and so forth. But there are many instances where the failure detection and isolation scheme is nonlinear too. In my opinion, there is just a complete lack of theory in that area and a complete lack of a methodology to solve the problem. We have worked for over a year and a half in this area under various contracts where we have derived the nonlinear GLR equations and came up with two or three ways to solve the problem.

We undertook an application that is a full blown six degree of freedom problem for a missile guidance control application. In that context, instead of the failure detection, the problem could be categorized one step higher in terms of an event detection and isolation scheme with the same equation and the same interpretation.

In this other application the event was a target maneuver which, as you can imagine, quickly becomes nonlinear. Just the geometry alone makes it nonlinear. Also, clever people can characterize many different things in this context. Any of the unknowns that you do not want to put in your model, because it would make it higher order or whatever, can be lumped into an event detection scheme. However, now what you have is more events to sort out in your algorithm. You could be processing events such as failures with events such as detecting changes in configuration, flight conditions, or anomalies, this sort of thing. So you could actually use one filter to process the many various things that are going on.

There are three basic ways in which one can approach the problem. One way is to do some prefiltering since many of these vehicles have INS systems and enough instruments to preprocess the events in such a way that they enter the filter algorithm in a linearized manner. That is one thing that we found to have a high payoff. It greatly simplifies the problem if it can be done at all. Another way is to linearize and gain schedule just like you do with your control laws. And yet another way is to directly solve this problem in real time, which is basically just as hard as a control problem in real time.

But you can see that the failure detection and estimation scheme is complicated enough without introducing nonlinearities. The complications, even in the linear case, arise from the fact that you have to do identification, estimation, and detection all at once. You have to separate the onset time of the particular event, as well as its magnitude and direction, and characterize it, and then you have to decide how to isolate it. So that appears to increase the dimension of any filter. You can have banks of Kalman filters going on right there in two or three dimensions. Now, add on top of that the nonlinear problem and you have got yourself some real problems to solve. It turned out that the application that we completed, the full-blown six degree of freedom, nonlinear scheme, was not as horrendous as we thought it would be. Once we were able to characterize the problem and do some scheduling, it turned out to be solvable. This was the basic worry that we had. We did not know whether we could do this because the equations, if you take them literally, are almost unsolvable. There are a lot of state-of-the-art techniques that people have used to reduce the dimensionality. Examples of these techniques are sliding windows and the clever characterization of events to reduce the number of events and parameters that need to be estimated.

In this example the geometry between the target and the aircraft or the missile brought nonlinearities into the system. And even the coordinate system in which you are going to write your equations becomes very important here. You might be clever enough to make a linear plant with nonlinear events entering your system. That is one way to do it. Or you have the choice of making a nonlinear plant with linear events entering in the system, depending on which coordinate frame you write your equations in. Both of these approaches have very sound mathematics but very different implications in terms of the eventual algorithm.

ROBUST FDI

- NASA Lewis Engine FDI Sensitive
- Can Take SV Approach
- MIT Theses

Another issue that I think needs to be addressed is robust failure detection and isolation schemes. There is a lot known about robust control systems and a lot of work has been done recently. Well, here we have a brand new topic to robustify. I know instances of failure detection/isolation schemes that work great with no mismatch conditions. But you mismatch them and they just go all to pot. A good example of this is the NASA Lewis engine failure detection and isolation scheme on the Pratt/Whitney F-100 engine that was recently published. It works well under normal conditions. Mismatch them at all and nothing works. But if you think about the problem, you can take the singular value (SV) approach and do robust designs of your filter. It is not the same as the control system problem because we are not dealing with a control system. But you can think about it that way and you can formulate the problem in an analogous way and come up with an analogous solution. In fact, there are two MIT dissertations published on that subject to date. Allan Willsky was the supervisor on both and he could provide this workshop with the material.

COORDINATE CONTROLLER, DETECTOR, ESTIMATOR, AND ISOLATOR

- MUST ALWAYS WORK WELL ALONE
- EXTREME CARE AND DESIGN ITERATION
- CONTROL BANDWIDTH DICTATES DESIGN MULTIRATE ESTIMATOR, DETECTOR, AND CORRECTOR
  - ONLY CORRECT WHEN NEEDED
  - PREMISE FOR OBSERVERS

Another area that I feel I cannot emphasize enough is coordinated control, detection, estimation, isolation, and identification. I have found in many applications that I have approached that people can pretty much get any one of them working well independent of the other. You know, people design good estimators, they have great full state feedback, and they have detectors based on sensors and geometry. They can just pull these right out. But you stick them all together and I have never seen anything work the first time. In fact, I have also seen people give up and say: "it is never going to work." The people who finally do make it work do it with a lot of sweat and iteration. As much as the modern control people like to think that it is just a cookbook procedure, I have never seen anybody put this together in cookbook fashion at all. The interconnection, the interfacing of these various techniques is ripe for study. I do not think anyone has properly addressed it to the point where each individual issue has been looked at. I can think of methodologies and ways to approach this that may be systematic. But I think we are far from there and that this is worthy of research on its own.

I also like Dave Downing's comments. I think he hit the nail right on the head. If this is an optimum control system, the control system ought to dictate to the rest of the software what it should do. For example, the control law bandwidth could pretty much be dictated by ultimate performance of the control system but when one independently goes and derives an estimator, filter, detector, whatever, they are done for the best detection or estimation scheme that they can produce. Well, that is just a bunch of baloney. They are there to support the control system. Getting them to work better does not mean that the control system is going to work better. I feel the control system should always have the upper hand at dictating that. There was another comment made about 'correcting only when necessary.' I think that there is a lot of merit in that. That way you can get the time requirements of the loops to be different. The outer, corrective loops should not, perhaps, be working as fast as the control system loops otherwise you have two things adapting to each other in the same time scales. The system may be able to tolerate some changes up to a threshold and then you make some corrections, and I think the system might ultimately be more stable that way. I also feel that there is a premise there for the design of observers in the first place. Observers do what you tell them to do; Kalman filters do not always do what you tell them to do. One can design an observer in a straightforward manner to be compatible with a control scheme and philosophy, whereas Kalman filters represent a whole new philosophy, a whole new scheme. And sometimes, in the control context, you cannot properly select filter input parameters.

AI / MODERN SYSTEMS THEORY

- TREE SEARCH FOR DECISIONS
- DECISION RULES FOR Q/R SELECTION

The fourth issue is the combination of artificial intelligence and modern systems theory. Mike Athans mentioned the tree searching algorithm for decisions but there is also an analogous, dual role in which you could use AI rules for picking Q and R matrices if you are ever thinking of doing that in real time. That is no more farfetched than tree searches because every thing may boil down to tree searching. The tree search is based on what the AI people call decision rules. Decision rules are nothing more than a smart man in a box. He has got a lot of smart things to say and, depending on what sequence the events occur in real time, he stacks these rules together and constructs trees. Well, these same kind of rules can be used to pick Q and R matrices. People have rules to do this right now. This sort of thing can be used to generate control schemes as the need arises in a point in time depending on the situation.

SENSOR FUSION

- CRLB FOR GEOMETRY AND SENSOR SELECTION
- MAY WANT INPUTS FROM PILOT
- INPUTS MAY BE HARD TO COMBINE OPTIMALLY
  - DECISIONS → ASSESSMENTS
  - SENSORS OF ALL SORTS
  - CAN VARY FROM ANY INSTANT (E.G., DAMAGE, PILOT)

Another issue is sensor fusion. I think we are talking about using many different sources of information all of which are not well formulated in today's filtering problem. Because you may be combining apples and oranges and that is sometimes hard to structure in an optimal sensor fusion problem.

The first comment I want to make in this area is that the Cramer-Rao Lower Bound (CRLB) study would be of paramount importance here for the initial geometry and sensor selection because you could actually determine the best a system could ever do without having to design an algorithm. This saves designing algorithms for all the systems except for the one you are eventually going to use. This also gives you a judgment as to how well the algorithm you are really going to design works according to the best it can do. The CRLB has been derived for the nonlinear case by Nils Sandell, and published in the IEEE Transactions on Automatic Control, and it formulates the equations for the nonlinear solution to the problem.

If you have inputs from the pilot into the system as well as from the sensors, it makes it a tough fusion problem because inputs from the pilot may be assessments from decisions he makes according to what he thinks the situation is. Well, another reason why, if time allows it, the pilot can input what he thinks is going on is because sometimes he is a better adaptive control system than the computer is. If the time scale is right, he has a role, and so, how do you fit that in with the outputs of a gyro? I think that this is a fundamental question that should not be overlooked.

Also, the sensors that your are using from time to time may be different. For example, damage may be occurring so you might have more or less sensors in the system at any one time depending on whether they are available, or whether they are even in the dynamic range and so forth. Or the pilot may be entering information sometimes and the time scale may not permit it and so the system has to do the best it can without it. So try to put that into an optimum scheme to determine the status of your system. That is nontrivial in itself.

MAN-MACHINE INTERACTION

- GREATEST INFLUENCE ON SYSTEM
- CAN ADAPT IF COORDINATED WELL
  - WHAT SHOULD BE KNOWN
  - WHAT DECISIONS SHOULD BE MADE
  - HOW SHOULD HE INTERACT WITH SYSTEM WITH HIS ASSESSMENTS

The man-machine interaction should not be overlooked because the greatest influence on the system is that of the pilot. I feel that the basic issues are: what should the pilot really know, what decisions should he be allowed to make, and how should he really interact with the system and its successors? These are fundamental questions that should not be overlooked as long as the pilot is going to be somewhere in the loop. And in many cases, like Three-Mile Island, there will be disaster once in a while when you do not take the human into account. It has turned out that the Babcock and Wilcox people could run that reactor just perfectly and never have a problem, but you have to design it for the persons who will operate it and the type of decisions you think they are going to make.

SUBMARINE CONTROL PHILOSOPHY

- ABILITY TO RECOVER FROM FAILURES DICTATES WHAT THE CONTROL SYSTEM IS ALLOWED TO DO
- "ANY ADDITIONAL CONTROL AUTHORITY IS JUST ANOTHER WAY TO GET IT TO THE BOTTOM."

The last issue is just an observation that would be interesting from the perspective of a submarine control system. This is a lot different and you have many more constraints. In fact, the basic difference that I see is that the failure modes dictate everything. The ability to recover from failures dictates what the control system is allowed to do. They will tell you right off, here is the control authority that you have and you are not allowed to have any more. I do not care if your control system is ten times better, you are not allowed to do this. An example is the limits that are in the bow and stern planes. They always can go up more than they can go down. The limit is set from the difference between operating depths and crush depths and how long it would take them to reverse the thrust to stop going down to the crush depth based on certain plane limits.

Well, although the problems are somewhat different, I thought that it would be interesting to make you aware of a situation in which the failure possibilities dictate everything.

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3.0 SUMMARY OF COMMENTS

At the conclusion of the workshop Mr. William Howell of the Applied Controls Branch, NASA LaRC, polled the attendees on their perception of the problem. Included herein is a summary of their comments.

Dr. Michael Athans, MIT.

- Enough theory is available to attack this problem, but we need to understand the robustness of these theories.
- A theory integration phase to find out the theories that will work together, should be an essential part of this program.
- Early flight simulation and test would be beneficial, but the simulation should be stochastic and include structural modes and severe wind gusts. Deterministic simulations do not provide a true test for the theories that need to be integrated in order to tackle this problem.

Dr. Tom Cunningham, Honeywell, Inc.

- There are a lot of theoretical techniques available to solve this problem.
- Take the existing theory and technology and extend them to design and demonstration of the concept.
- There should be theoretical work as part of the program, but this is not needed as the basis of the program.
- Early flight demonstration, experimentation, and evaluation is absolutely essential and may serve as a pointer and/or driver for needed further theoretical development.

Dr. David Downing, University of Kansas.

- Carry the flight critical concepts that will emerge from work in this area through flight demonstrations or verification. We must show that these concepts will work in the real world.

Mr. Edmund G. Rynaski, Calspan.

- The major bottleneck problem was recognized by everyone, I believe, as being the detection problem. Because we are considering a very low probability event, it will be difficult to formulate a detection strategy in which the occurrence of the event will happen more often than a false alarm or failure of the detection mechanism itself.

- Determine the importance of the role of the pilot in the control restructuring problem. Depending on the time frame and flight condition the pilot may:

  - be in the loop aided by system-derived information
  - be off the loop with the system completely automatic (takeoffs and landings).

- Determine the basic control configuration that would allow restructuring to take place.

- Determine the impact on the basic design of aircraft to be able to achieve restructuring most effectively.

- Flight testing is essential as a precursor to or in parallel with the development of supporting theory.

Dr. V. Klein, George Washington University.

- On-line system identification should be a part of a restructurable control system.

- Theoretical work needs to be done on the robustness of the algorithms to modeling errors and to the effect of the feedback environment.

- All developed techniques must be tested on-line in the real world.

Peter Briggs, General Electric Company.

- Elements of the current Air Force program on Self-Repairing Digital Flight Control Systems will be available for application to the next fighter and transport aircraft (early 1990's).

- In order to make this application realistic advances in two other technologies must come to a timely confluence, software technology and processor hardware technology. Government should continue to stimulate development in these two technologies as well as the development of a High Order Programming Language to facilitate implementation of complex digital control systems.

Jarrell Elliott, NASA LaRC.

- Acceptable configuration of the system after failure affects the definition of the problem and the way to deal with it. Restructurable controls in civilian aircraft is different than in military aircraft.

- A basic approach to the problem should be the implementation of an automatic reaction system (a regulator perhaps) which would control the aircraft with the remaining controls and which buys time for the pilot to assess the situation and take corrective action.

- Implement means to automatically assess the situation and display information to the pilot which will aid him in taking proper actions and avoid improper actions.

- There is a need to identify some short term goals and some long term goals so that areas of the problem can be separated. In the process, identify those areas that will require further theoretical development.

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APPENDIX A. DELTA FLIGHT 1080 STORY

A.1 Letter From Captain McMahan

Captain Jack McMahan of Delta Airlines was invited to attend the workshop. Although he was not able to attend, he sent a letter to the organizer summarizing the Delta Flight 1080 incident. This letter is included in this appendix.

September 8, 1982
2045 Renault Lane
Atlanta, GA 30345

Mr. William E. Howell
NASA

Dear Mr. Howell,

I received the information regarding the workshop on Restructurable Controls to be held on September 21-22, 1982. As I mentioned in our recent telephone conversation, I regretfully will be unable to attend due to a prior commitment on these dates.

Enclosed is the story/history of Flight 1080 as published in the Airline Pilots Magazine, along with a couple of documents I thought might be of interest to your group.

With the left elevator jammed 19° up, I experienced not only a pitching moment but also the aircraft had a strong rolling tendency to the left--I was up against the control stops in pitch and occasionally in roll when attempting a right bank. I also thought of "split spoilers" and under the stress of the incident, there was not time to analyze which set of spoiler panels to deactivate and I was not sure of our hydraulic system integrity--if a mistake was made, there was no published procedure, we would have been in worse shape than ever.

I might add that essentially I flew the aircraft with the throttles--Number #2 advanced to assist pitch and Number #1 following #2 to offset roll and followed by Number #3. ▤▨▤ something like this.

If I can be of further assistance in this study, please do not hesitate to call on me.

Sincerely,

Jack McMahan

APPENDIX A

A.2*

Flight 1080

> **"As pilot-in-command of Delta Air Lines Flight 1080, he maneuvered his malfunctioning aircraft more than 100 miles through 8,000 feet of solid overcast to a safe landing. His professional judgment and skill merit the gratitude of America's flying public."**

From Distinguished Service Award presented by the Federal Aviation Administration to Capt. Jack McMahan, August 1977

By Capt. Jack McMahan (DAL)

On April 12, 1977, I was the captain of Delta Flight 1080 which experienced, on the San Diego to Los Angeles leg, a serious control problem in the pitch axis immediately after takeoff. At night, overwater and on instruments, it appeared to be almost certain disaster.

At departure time, the San Diego weather was reported as 800 feet overcast, visibility 5 miles, temperature 58°F, wind 260° at 8 knots. The L-1011's gross weight was 300,000 pounds with 42,000 pounds of fuel, 41 passengers and a crew of 11. The following takeoff data was applicable: V_1—123 knots; V_R—126 knots; V_2—138 knots; 3.5° stabilizer setting; 28% mean aerodynamic chord; 1.465 engine pressure ratio—alternate thrust.

The other flight crew members were First Officer Will Radford and Second Officer Steve Heidt.

During taxi out, Will performed a flight control check of the stabilizer, ailerons and spoilers while I made the rudder check. The proper control response was verified by the SPI (surface position indicator) and no abnormal control "feel" was experienced. The flight controls on the L-1011 are fully hydraulic using four separate and independent 3,000 PSI (pounds per square inch) hydraulic systems.

The visibility appeared to be deteriorating. I recall thinking that the San Diego and Los Angeles weather would probably be at or near minimums within a couple of hours as the entire coastline had a heavy stratus deck moving onshore.

The flight departed San Diego at 23:53 Pacific standard time, an overwater departure to the west on Runway 27. The clearance was a Scorpion Six departure to Los Angeles at an assigned altitude of 10,000 feet.

During the takeoff roll, quite a bit of aircraft vibration was experienced due to the roughness of Runway 27. I relaxed forward pressure on the control column and reduced the vibration somewhat. Acceleration was normal, but at V_R of 126 knots, the aircraft lifted off with little or no control input and a zero stick force. Immediately after liftoff an abrupt nose-high excursion in pitch was experienced that was controllable although I did hit the full forward limit of the control column during this abrupt pitch up. I quickly doublechecked the stabilizer setting. It was correctly set at 3.5° aircraft nose up. Climb attitude of 15° pitch was reestablished with air speed increasing, gear retracted and landing lights extinguished. The aircraft appeared to return to a normal takeoff flight profile.

Check and doublecheck

At an altitude of approximately 400 feet and an air speed of 168 to 170 knots, the pitch started to become excessive, exceeding 15° to 18°. I was exerting a light push force on the control column and trimming electrically by use of thumbwheel trim when the thumbwheel movement stopped. The pitch controls felt very sluggish and I immediately attempted to utilize the mechanical trimwheel which serves as a back-up system and overides the electric trim. There was no response with the mechanical trim. I found that the trim was already zeroed out with full nose-down stabilizer trim as indicated on the stabilizer trim indices and

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zero stabilizer indicated on the SPI instrument. I reset the electric trim switches with no effect; the thumbwheel trim remained immovable.

At this time we went on instruments at 800 feet MSL (mean sea level) and I started a right turn on course. I remarked to Will that I was having trim problems and asked Steve to check the hydraulic system. I was not overly concerned at this time as the L-1011 has a fine primary flight control system consisting of a flying stabilizer, four independent hydraulic systems, a well designed light legend to alert the pilot of a malfunction and plenty of redundancy in the system. I was confident that one of several possible procedures would correct our pitch problem.

I unlatched and reset all switches associated with trim—pitch trim, mach trim and pitch trim monitor—with no effect. Will conducted an area test of the switchlights to verify light integrity as there were no lights illuminated on the various panels. Steve double-checked hydraulics and checked for any opened circuit breakers. By 3,000 MSL, all emergency procedures for trim, pitch axis jam, flight control path jam and hydraulic malfunction were exhausted with no effect on controllability.

San Diego Departure Control was informed that we were experiencing a pitch problem and was asked to stay with us. Later we received a handoff to Coast Approach.

The first officer and I both were on the controls at this time and exerting full forward force on the control column. The aircraft continued to pitch up and air speed continued to decrease. I recall observing 3,000 feet-3,500 feet-4,500 feet on the altimeter. Pitch attitude exceeding 18°-20°-22°. Air speed decaying: 150-145-143-140. Then an air speed of slightly less than the V_2 speed of 138 knots. We were also experiencing a roll problem. In attempting to maintain a right bank, I hit the stops a couple of times in roll control.

Can't 'fly'

Suddenly, I had the horrifying realization that the loss of the aircraft was imminent. (Will and Steve later expressed the same opinion.) It appeared certain that the aircraft would enter a stall and, having no control over pitch to affect recovery, crash into the ocean.

It is remarkable how the mind functions during periods of extreme stress. Many thoughts race through your mind which can later be recalled with amazing clarity. When it became apparent that we were in deep trouble, my first thought was "I have always emphasized the mental discipline of 'fly the aircraft' and I can't even 'fly' this one."

Then, a very unusual experience occurred. I had a clear mental picture of exactly what the aircraft was going to do—stall, roll to the left and descend vertically disappearing into the clouds—at night—over water. The sensation was as if I was outside the aircraft observing it from some distance away. I remember thinking of the triumvirate theory: accidents occur in series of threes. There was the Canary Islands accident involving KLM and Pan Am, then the Southern DC-9 at New Hope, Ga. I thought we were about to become the third!

Finally, I recall thinking: "We are going to crash into the ocean and no one will ever know what happened. Inevitably the conclusion will be *pilot error*. 'Pilot became disoriented while executing a night overwater takeoff and encountering instrument conditions.'" I have read this statement a number of times as the probable cause of an accident.

Suddenly I was jolted back to reality: "Wait just a minute—as many night over-water takeoffs and landings as I have made! We may lose this aircraft, but it won't be because we're not hanging in there and it won't be because of pilot error."

At this instant, I felt an intense compassion for my passengers and fellow crew members. Their lives, their safety, were my responsibility. Perhaps this selflessness is the catalyst that provides the inner strength or starts the adrenalin pump, permitting one to overcome impossible circumstances.

"Thrust is affecting pitch. Drag is affecting air speed. If I can reduce pitch, if I can regain air speed," I thought, "we might have a chance to recover some degree of controllability."

I abruptly reduced thrust on all three engines and recognized a modest change in control "feel." I then advanced No. 2 throttle full forward. Will called my attention to the No. 2 engine pressure ratio and I recall observing a 1.565 reading. Almost simultaneously, I had to increase thrust on engines 1 and 3 to prevent any further loss of air speed. I observed pitch correcting back through 20° to somewhere around 18° and the air speed slowly increasing above 140 knots. I had to further increase thrust on the No. 1 engine to compensate for a left roll tendency. I felt certain that we were about to recover from a most desperate situation.

As soon as possible, about 150 knots, the flaps were retracted from 10° (takeoff setting) to 4° and the air speed started to increase at a better rate. Performance data called for 198 knots (V_{REF} + 60) before going to the clean configuration.

Moonlight and momentary relief

Will and I both were still exerting full forward pressure on the control column and the pitch attitude remained at 18° to 20° nose high. Steve made a full scan of all the circuit breakers and switchlight panels in a futile attempt to determine the nature of the malfunction.

Radio contact with Coast Approach was established and they were informed that we were experiencing control problems. They acknowledged immediately with a proffer of assistance and we were cleared direct to Seal Beach VOR to maintain 10,000 feet. I recall methodically returning my VOR receiver to 115.7 MH as if we had no problems whatsoever, then resetting the heading select mode and realigning the VOR radial.

At an altitude of approximately 9,000 feet, we broke out of the overcast into the clear with quite a bit of moonlight—a very welcome change from the solid instrument conditions we had encountered. I had been having a difficult time just coping with the conditions, in addition to attempting to identify the problem and execute emergency procedures.

At about the same time as reaching on top of the clouds, the air speed had increased sufficiently and the remaining 4° flaps were retracted. With an indicated air speed of approximately 190 knots, still climbing sharply with no control over pitch, it became evident that the aircraft would climb right on through our assigned altitude of 10,000 feet. Coast Approach was advised and they responded with a block altitude of 10,000 feet to 12,000 feet. Climbing through 11,500 feet with no improvement in our ability to control pitch, it was apparent that we could not maintain 12,000 feet either. We informed Coast Approach and they very cooperatively replied, "We have you on radar and all altitudes are clear. We will stay with you."

The aircraft continued to climb steeply even though Will and I had the control column full forward, almost touching the instrument panel. My mind reeled: "We recovered from the worst condition when it appeared certain that the aircraft was going to stall around 5,000 feet, now the problem is we can't stop the climb and, if I don't do something rather quickly, this aircraft is going to climb to some unknown altitude, 25,000 or even 30,000 feet, then run out of air speed and controllability and descend as steeply as it went up."

Approaching an altitude of 14,000 feet, I had no alternative except to retard the thrust on Engines 1 and 3. The aircraft slowly responded with a slight pitch change and I attempted to descend back to 10,000 feet. I was unable to stop the descent rate at 10,000 feet, but with constant power adjustment I was able to regain control at 9,500 feet. Then we were back up to 10,400 feet, then below 10,000 feet again and finally fairly well stabilized at 10,000 feet.

The pitch attitude to maintain level flight was 12° to 14° with thrust equivalent to climb power due to the induced drag. The air speed stabilized at 195 to 197 knots. The throttles were severely staggered to maintain control over pitch and a roll tendency. No. 2 throttle was well in advance of No. 1 and No. 1 in advance of No. 3 throttle. The air speed had to be controlled below 200 knots or the aircraft would again start climbing. I was quite concerned about the extreme nose high attitude of 12° to 14° pitch and the amount of thrust required to maintain level flight. It appeared that we were working within a narrow air speed envelope—too fast and control over pitch and altitude was impossible, too slow and a stall would occur.

Again, all emergency procedures were doublechecked in a futile attempt to identify the nature of the problem. There were no known procedures relating to the malfunction we were experiencing.

The flight attendants were briefed on the situation at this time. We told them we had a control problem, but that it was now pretty well under control and they should not be overly concerned about the unusually high deck angle. In an attempt to improve the center of gravity, we asked them to move all the passengers forward and, as a precaution, to position them as near the emergency exits as possible. We assured them we would keep them fully informed of our progress and course of action.

Now the decision had to be made where to go from here. Our position was halfway between San Diego and Los Angeles. We had our hands full with a partially disabled aircraft, which we had to attempt to get safely on the ground, but where?

Low ceilings, poor visibility and a heavy overcast predominated the coastal region, virtually eliminating Los Angeles, Long Beach and El Toro airports. San Diego was out of the question—no way I was going back into those conditions. The weather was good on the eastern side of the mountains and my first choice was Palmdale Air Force Plant or Edwards

Air Force Base. However, it was now well after midnight and I knew that both of these facilities normally close down at 10 p.m. and that their control towers are not staffed during this period. It would take considerable time to alert the tower personnel, turn the runway lights on and have the emergency equipment standing by. Time, related to fuel, now became a critical factor.

Las Vegas and Phoenix were also considered as possible available airports, but fuel and the high minimum enroute altitude along these routes presented a major problem. Altitudes of 11,000 feet to 13,000 feet are necessary for terrain clearance in these areas, which would require us to climb. And there was a strong possibility of encountering turbulence enroute. With our limited control over the aircraft, any encounter with turbulence might easily cause us to lose control altogether.

The decision to proceed to Los Angeles, even though the weather was marginal (700 feet and 4 miles visibility) was made primarily due to our rather limited options. Most importantly, we were stabilized in smooth air and over water, with plenty of altitude to work with in the event we had further difficulties, and Los Angeles offered our best chance for a long, straight-in, stabilized approach to Runway 6R. It's an approach I was very familiar with—a strong plus factor.

We contacted Los Angeles Air Route Traffic Control, declared an emergency, explained our control problems and requested a 15 to 18-mile straight-in approach to 6R.

Prepare for the worst

The flight attendants were briefed on the landing plans and instructed to prepare for emergency evacuation of the passengers. A water ditching was a possibility and a land evacuation a probability. We told them to prepare for the worst and hope for the best. In a low-key manner an announcement was made to the passengers that, in accordance with company procedures, precautionary measures were being taken to insure their safety and that we would be landing in Los Angeles in a few minutes.

The next question was: "How do we land this aircraft? Obviously we have very little pitch control, we have a roll problem, none of the emergency or abnormal procedures have been effective. Why isn't the stabilizer more effective? The huge flying tail of the L-1011 has a tremendous amount of authority in pitch; the aircraft is trimmed full nose down—why no response? Do we have a spoiler problem causing the roll? Is the problem hydraulic?"

We had a confounding number of unanswered questions.

I thought a normal landing utilizing 33° flaps and an air speed pad of perhaps 10 to 12 knots would not be feasible for a number of reasons. I was afraid that on landing, with no control over pitch, when the aircraft entered ground effect I would not be able to force it on the runway and we might float all the way across the airport. Or worse, when we set up the landing flare the aircraft might pitch up to an altitude of 200 or 300 feet, stall and crash. And we would be helpless to prevent it.

Another consideration was the thrust/drag curve during the approach. If we got behind the power curve, would there be enough thrust to overcome drag and still be able to control the aircraft? My evaluation was that there was a strong possibility we might reach an altitude of 400 or 500 feet during the approach and lose control. This reasoning was also a major consideration in selecting the west to east approach to Runway 6R at Los Angeles. We elected to remain over water to avoid endangering lives and property on the ground. Although landing east to west on Runway 24 is a better approach, it is over residential areas. I had a mental picture of what a holocaust this could create. I thought to myself, if we lose it, we lose it over water.

I decided that we would try one step at a time, using incremental flaps, verifying pitch control with each increment and attempting to establish a configuration of 22° flaps and an air speed of 165 knots for the approach and landing. At 4° flaps the aircraft pitched down slightly and I was able to recover about one-half inch of control column movement from the full forward limit. At 10° flaps the additional pitch-down gave me another half inch of control response. The aircraft was stabilized at 180 knots, 10° flaps, 12° pitch, and one inch of control movement was available. Even though we were still severely limited, this felt like a major accomplishment.

I tried the autopilot to determine if it had some trim authority we might utilize. The aircraft pitched up immediately and the autopilot was disengaged.

While maintaining 180 knots air speed and the 10° flap configuration, we were able to maneuver the aircraft reasonably well and follow radar vectors to position for a 6R instrument approach.

Instrument conditions were again encountered at approximately 9,000 feet during descent. We continued to 5,000 feet and intercepted 6R runway instrument localizer and glide slope 15 miles from the runway threshold. The approach was made with 10° flaps and 180 knots indicated air speed with a sink rate of 800 feet to 900 feet per minute. The pitch attitude was 10° to 12° nose up, and I recall thinking that we might experience a tail strike at touchdown. Autoground spoilers were disarmed to prevent any additional pitch-up tendency on landing.

Steve informed the flight attendants that we would be on the ground shortly and to be prepared for a possible emergency evacuation on our signal. Steve also made a reassuring announcement to the passengers.

We had it made—almost

The instrument approach was initiated and going very well. I was able to maintain the target air speed of 180 knots and control the sink rate to remain on glide slope with the limited pitch control and varying thrust. The approach checklist was completed and for the first time since departing San Diego I felt we more or less "had it made." All we had to do was extend the landing gear, make a flap change to 22°, break out, establish visual contact with the runway and land the aircraft.

Then, at 2,500 feet, when the landing gear was extended, the aircraft again pitched up. I shoved the control column full forward but the aircraft continued to climb while the air speed deteriorated, and we were going above the glide slope.

My first thought was: "Since we can't control the aircraft with the gear down, retract the gear, turn to a south heading and ditch in the ocean parallel to the coastline."

I felt that it would be impossible to control a missed approach or a go-around and that this was a "one shot" attempt. We were so close and yet so far; again in serious difficulty and on the verge of disaster.

Once more I increased thrust on No. 2 engine, reduced thrust on engines 1 and 3. The aircraft responded slowly and I was able to maneuver back down to reestablish glide slope tracking. The flying was a little rough in this area, a major power change was required to stop the climb and get a descent restarted and to attempt to capture glide slope. I left the landing gear extended, selected 18° flaps, and the air speed stabilized at 170 knots.

Upon reaching 700 feet, we broke out of the overcast and visual contact with the runway was established. We were aligned with the runway and had a sink rate of 800 to 900 feet per minute, which was going to be perfect for my touchdown reference point. I was not going to attempt a flare—just fly the aircraft to touchdown. I abandoned the thought of using 22° flaps. Things were going so well, I thought, "Don't change a thing—just get it on the ground!"

Touchdown was made at approximately 165 to 170 knots indicated air speed in the first 1,000 feet of Runway 6R. After main gear contact, the nose did not come down, and I could not force the nose over with the control column full forward. It was necessary to apply main-wheel braking in order to force the nose wheel down.

After 55 minutes of airborne time, we were on the ground.

I applied reverse thrust on engines 1 and 3 and reverse idle on No. 2, since heavy reverse thrust on the No. 2 engine tends to pitch the nose up. I'd had enough pitch-ups for one day.

No tail strikes. No blown tires. We exited the runway at taxiway No. 47 and taxied to the ramp.

The malfunction was determined to be the left elevator jammed in the "up" position. Presumably the left elevator aft drive quadrant (Bell crank) and drive cable failed during the flight control check prior to takeoff. There is no cockpit indication for this type of failure on the L-1011.

An equipment substitution was provided, and the crew and passengers continued Flight 1080 without further incident. ☐

AIR LINE PILOT July 1978

APPENDIX B. AMERICAN AIRLINES DC-10 CRASH IN CHICAGO

This appendix presents excerpts from the National Transportation Safety Board Accident Report on the American Airlines DC-10 crash at Chicago-O'Hare International Airport on May 25, 1979 (NTSB-AAR-79-17, Dec. 21, 1979).

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pp 23-24:

Each of the thirteen pilots who participated in the simulation was thoroughly briefed on the flight profile of Flight 191. In the simulator the No. 1 engine and pylon assembly was programmed to separate at 10° of rotation on all takeoffs with simultaneous loss of the No. 1 hydraulic system. On some test runs the No. 3 hydraulic system was also programmed to fail. Generally, slats began to retract about 1 sec after the engine and pylon separated and were fully closed in about 2 sec. Some test runs were conducted with the slat retraction beginning 10 to 20 sec after the engine and pylon separated. Speed control guidance from the flight director was available for all runs, and the stickshaker, programmed for the slat-retracted-airspeed schedule, was operational on some runs.

During the tests, about 70 takeoffs and 2 simulated landings were conducted. In all cases where the pilots duplicated the control inputs and pitch attitudes shown on the Flight 191's DFDR, control of the aircraft was lost and Flight 191's flight profile was duplicated. Those pilots who attempted to track the flight director's pitch command bars also duplicated Flight 191's DFDR profile.

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In many cases, the pilots, upon recognizing the start of the roll at a constant pitch attitude, lowered the nose, increased airspeed, recovered, and continued flight. The roll angles were less than 30°, and about 80 percent right rudder and 70 percent right-wing-down aileron were required for recovery. In those cases where the pilot attempted to regain the 14° pitch attitude commanded by the flight director command bars, the aircraft reentered the left roll.

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pp 54–55:

The simulator tests showed that the aircraft could have been flown successfully at speeds above 159 KIAS, or if the roll onset was recognized as a stall, the nose could have been lowered, and the aircraft accelerated out of the stall regime. However, the stall warning system, which provided a warning based on the 159 KIAS stall speed, was functioning on the successful simulator flights. Although several pilots were able to recover control of the aircraft after the roll began, these pilots were all aware of the circumstances of the accident. All participating pilots agreed that based upon the accident circumstances and the lack of available warning systems, it was not reasonable to expect the pilots of Flight 191 either to have recognized the beginning of the roll as a stall or to recover from the roll. The Safety Board concurs.

In addition, the simulator tests showed that the aircraft could have been landed safely in its accident configuration using then current American Airlines procedures. The simulator tests also disclosed that the aircraft could have been landed with an asymmetric leading edge slat configuration. The speed margins during the final positions of the landing approach are also very small; however, the landing situation is considered less critical since additional thrust is readily available as required to either adjust the flightpath or accelerate the aircraft. In addition, service experience has shown that loss of slats on one wing during the approach presents no significant control problems.

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In summary, the loss of control of the aircraft was caused by the combination of three events: the retraction of the left wing's outboard leading edge slats; the loss of the slat disagreement warning system; and the loss of the stall warning system -- all resulting from the separation of the engine pylon assembly. Each by itself would not have caused a qualified flightcrew to lose control of its aircraft, but together during a critical portion of flight, they created a situation which afforded the flightcrew an inadequate opportunity to recognize and prevent the ensuing stall of the aircraft.

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15. Supplementary Notes

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16. Abstract

Future aircraft with highly sophisticated controls are likely to have multiple interdependent failure modes which will be more difficult for the pilot to recognize. Such failure modes are more likely to lead to unanticipated sequences of events for which the solution is not intuitively clear to the pilot. Furthermore, it may be impossible to recognize all of these modes during the design.

These proceedings document the Workshop on Restructurable Controls held at NASA Langley Research Center, September 21-22, 1982. The workshop examined the possibilities of combining various advanced technologies to provide on-line assistance to pilots dependent on flight-crucial controls when anticipated or unanticipated failures occur. In the first case, it may be beneficial to reconfigure the aircraft controls with previously stored alternatives, and in the second case it may be possible to restructure the controls using a combination of technologies. Applicable technologies include failure detection and isolation methods, parameter identification techniques, and modern control theory. Significant effort is required to integrate these into a plausible approach.

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